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Evaluating the Effects of Low Impact Development on Texas A&M University West Campus

By

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Abstract

Evaluating the Effects of Low Impact Development on Texas A&M University West Campus

The west campus of Texas A&M University is located in the White Creek watershed and has experienced increases in urbanization in recent years. This urbanization has dramatically impacted White Creek, including bank erosion from higher runoff volumes and peak flows. This study uses HEC-HMS and SWMM models to evaluate the effectiveness of low impact development (LID) and best management practices (BMP) in lowering runoff volumes and peak flows on the Texas A&M Campus. The LID techniques evaluated were green roofs, rainwater harvesting and pervious pavements and the BMP evaluated was a detention pond. A new metric, the Hydrologic Footprint Residence, developed by Giacomoni and Zechman (2009) is used for further comparison. HFR incorporates the quantity of flow from a storm with the cross sections of the stream to determine the flood area. This flood area is plotted with respect to time and the area under the curve represents the HFR, in area-time. The LID and BMP technologies were applied to the watershed and evaluated using 77 historical precipitation events. A set of 10 representative storms were used for analysis. In general, the scenario that was the most effective in lowering the peak flow, runoff volume, and HFR of the storm was the combination of rainwater harvesting and pervious pavements. The detention pond was shown to effectively lower the peak flow for larger storms, but does not change the runoff volume of any storm. The LID techniques were shown to be more effective in reducing the impacts of urbanization for small storms. The results also gave insight into the importance of the precipitation intensity and duration. The importance of the Antecedent Moisture Condition of the soil is evaluated in the second part of the study. The AMC was found to have an impact on the peak flows with AMCIII (saturated soil) resulting in the highest peak flow for each storm event and AMCI (dry soil) resulting in lowest peak flow.

Table of Contents

List of Tables

List of Figures

BACKGROUND

Urban land area in the U.S. more than quadrupled between 1945 and 1997, increasing from 15 million acres to 64 million acres. The new urban area was previously forested, pastured, and ranged land (U.S. Department of Agriculture 2000). Urbanization is accompanied by increases in impervious areas from roadways, parking lots and buildings. The impervious area replaces undeveloped land, altering the hydrologic cycle. These alterations can result in increased peak flows conditions and flood events (Clar 2003). The watershed can also have reduced ability to mitigate floods, facilitate sediment replenishment, and protect water quality and aquatic health by removing excess nutrients and other chemical contaminants before runoff enters receiving waters (Guitierrez 2006). The hydrologic regime is also impaired through more frequent and longer bankfull events, lower baseflows, and increased stream channel erosion from higher peak flows and runoff volumes (Guitierrez 2006).

Engineers have developed several methods to alleviate the negative effects of urbanization on a watershed. The main objective is to restore the hydrologic regime as close as possible to the undeveloped conditions. Other goals include mitigating sediment transport and water quality issues depending on the site. The methods can be broken into two categories: Best Management Plans (BMPs) and Low Impact Development techniques (LID).

The EPA's approach is to control the runoff volume and peak flows by using BMPs. Structural BMPs are designed to trap and detain runoff to settle or filter out the constituents before they enter receiving waters (Guitierrez 2006). Detention ponds are a structural BMP that retain runoff that otherwise would go into receiving waters directly, thus reducing the peak flow. Detention ponds are designed to retain the runoff while slowly releasing it; therefore, the same volume of water will enter the receiving waters. The detention ponds also use gravity sedimentation of the stormwater constituents to treat the water (American Society of Civil Engineers 2006). Detention ponds require open space, which may not always be available in highly urbanized areas.

Low Impact Development is a relatively new concept that focuses on replicating the predevelopment hydrologic regime and controlling the stormwater at the source. LID uses design techniques centered on integrated and micro-scale stormwater retention and detention areas, reduction in impervious surfaces, and the lengthening of flow paths and runoff times (Bitting and Kloss 2008). An advantage to LID techniques is the potential to retrofit existing structures and urban areas. LID techniques include green roofs, bioretention, grass swales, rainwater harvesting, pervious pavement, and infiltration trenches.

Green roofs are a LID technique that can be placed on existing structures, making it an ideal application in urban areas. Green roofs are planters placed on flat or low sloping roofs that contain absorbent growing media and drainage materials to support plant communities (Seymour, et al. 2007). The plants chosen are typically native to the region and can withstand extreme weather conditions on the roof. The primary function of green roofs is to prevent and reduce runoff through detention of the rainwater. Green roofs can also improve water quality by acting as a filter for the stormwater. For storms with less than 1 in of precipitation, green roofs can provide complete retention, and for larger storms the plants behave as detention ponds to provide storage and slow release. The detention allows for dampening of the storm surge normally associated with impervious rooftops during rainfall events (Hilten and Lawrence 2007).

Rainwater harvesting incorporates the use of rain barrels or storage tanks connected directly to the gutters and rainspouts of a building. The main functions of rainwater harvesting are the detention of rainwater which reduces the peak discharge and runoff volume (Coffman and Clar 2003). The rain barrels collect rainwater runoff from the catchment area and detain the water for later irrigation use or other non-potable uses.

Pervious pavement is a LID technique that replaces traditional roads and parking lots with structurally strong pervious surface materials underlain by a stone bed. This stone bed provides stormwater storage for infiltration under the pavement structure (Seymour, et al. 2007). When rainwater hits the pervious pavements, it can infiltrate down through the pore spaces in the pavement instead of running off the pavement in sheet flow. Through quick infiltration rates, pervious pavements are effective at lowering runoff volume and peak flow (Seymour, et al. 2007). Depending on the materials used, pervious pavements can also improve runoff quality when contaminants become trapped in the pore spaces. Pervious pavements are ideal in urban settings because they greatly reduce nonporous surfaces.

INTRODUCTION

Texas A&M University is located in College Station, TX on the White Creek watershed. The University has experienced a large growth over the past 40 years with an increase in the student body from 7,500 students in 1962 to over 52,000 students in 2004 (Barnes Gromatzky Kosarek Architects and Micheal Dennis and Associates 2004). To accommodate the growing student population, new buildings and parking lots were built on the West Campus of Texas A&M University resulting in an impervious area increase to 41% of the watershed (Damodaram, et al. 2010). This growth has resulted in the deterioration of the White Creek watershed. The increase in runoff due to the urbanization in the watershed has led to many problems. The creek and its tributaries have experienced extensive erosion that has come precariously close to buildings. The study site is approximately 4.4 square kilometers, and can be seen in Figure 1.

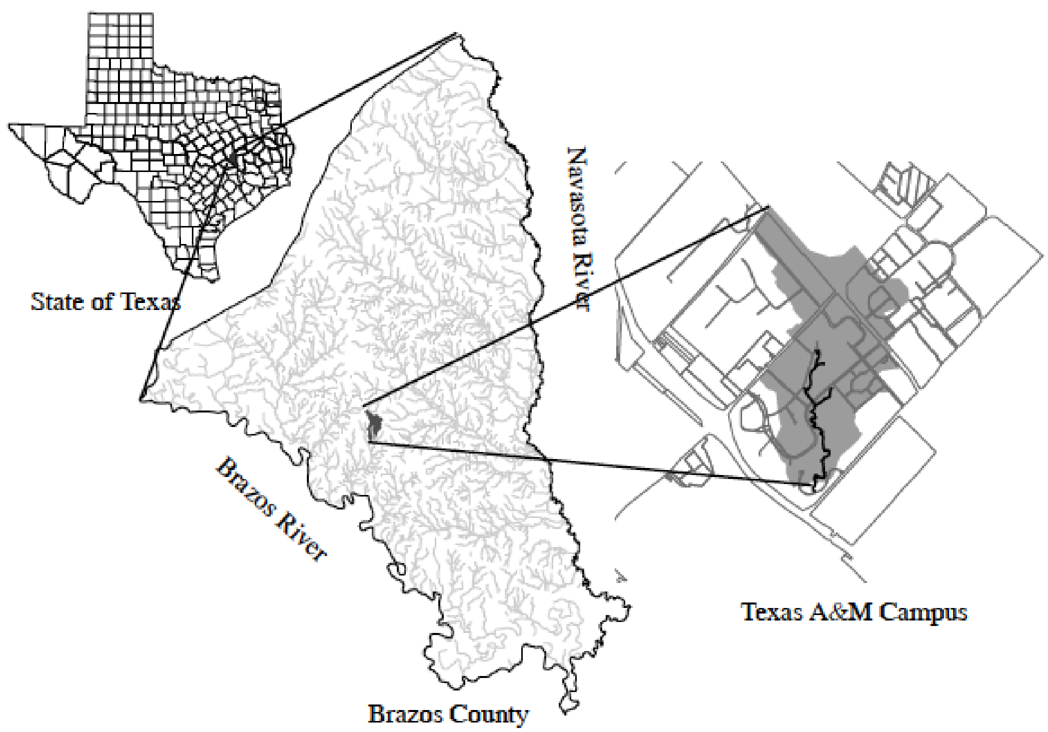


Figure 1: Texas A&M University West Campus and Study Site of White Creek (Giacomoni and Zechman 2009)

This study evaluates the impact of implementing several Low Impact Development (LID) techniques and Best Management Practices (BMP) on the Texas A&M campus. The LID techniques considered are rainwater harvesting, pervious pavements, and green roofs. These techniques were chosen because they can be retrofitted on the existing urban infrastructure. The BMP that was considered was a detention pond. This study evaluates seven scenarios on their effectiveness to lower the peak discharge and runoff volumes. These scenarios can be seen in Table 1. The scenarios were also compared using a new metric called Hydrologic Footprint Residence (HFR) developed by Giacomoni and Zechman (2009). HFR is different than previous metrics such as peak flow because it attempts to capture the extent of hydrologic change and impact on downstream communities. HFR uses the runoff volume and flow from a given rainfall event. It combines this data with the cross-sections of the stream to find the area of each reach that is flooded. The areas are calculated for each time step over the storm duration to determine the land inundated by flooding and duration of the flood's residence. HFR is represented by a single number with units, area-hours. Figure 2 shows the process by which HFR is calculated for a watershed.

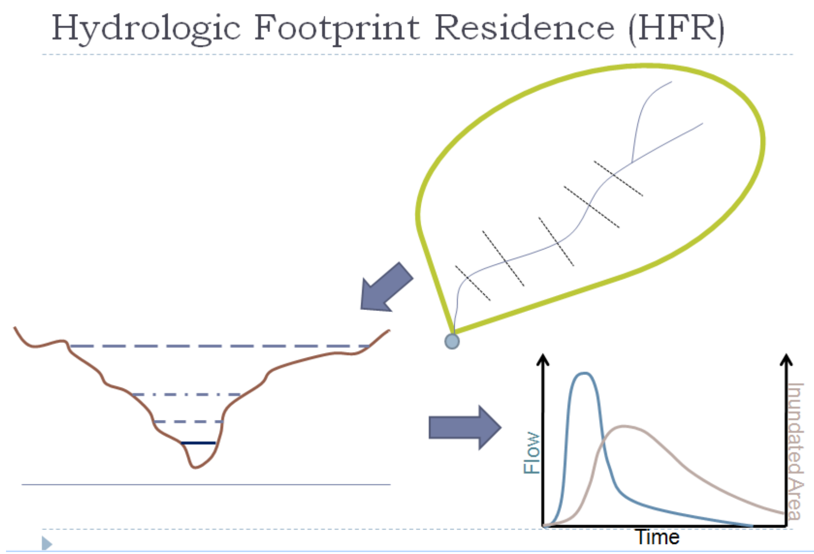


Figure 2: Hydrologic Footprint Residence Methodology: Rainfall falls on a watershed. The hydrologic and hydraulic models of the watershed are used to determine the runoff quantity. The runoff quantity is then used with the cross sections of the stream to find the inundated area at each time step. The HFR value is the total inundated area- time which is quantified by the area under the graph.

The scenarios evaluated can be seen in Table 1. The software used to model the hydrology of the watershed was Hydrologic Modeling System (HEC-HMS) and Storm Water Management Model (SWMM). The HFR was determined using a Microsoft Visual Basic Code in Microsoft Excel written by Giacomoni and Zechman (2009).[1] HFR was intended to evaluate the modification of a watershed and duration of a flood's residence. It can also be used to evaluate hydrological changes and develop management plans (Giacomoni and Zechman 2009).

[1] Please direct further questions about the HFR code to Dr. Emily Zechman, Assistant Professor of Civil Engineering at Texas A&M University.

Scenario	Description
Present	Current conditions of the Texas A&M Campus
Green Roof	Green Roofs applied to the potential buildings on Texas A&M Campus
Rainwater Harvesting	Rainwater Harvesting applied to potential buildings on Texas A&M Campus
Pervious Pavement	Pervious Pavements applied to parking lots on Texas A&M Campus
Green Roof & Pervious Pavement	Green Roofs and Pervious Pavements applied to buildings and parking lots
Rainwater Harvesting & Pervious Pavement	Rainwater Harvesting and Pervious Pavements applied to buildings and parking lots
Detention Pond	Detention pond with volume of 73,372 m^3 applied to Texas A&M Campus

Table 1: 7 Scenarios used in this study

PROCEDURE

This study is a continuation of a larger project by Dr. Emily Zechman and several students at Texas A&M University. The present study was broken into two parts. The first study part evaluated the seven scenarios described in Table 1 under 77 historical precipitation events. These scenarios were evaluated and the results compared using the runoff volume, peak discharge and HFR of the watershed. The second study part evaluated the importance of the Antecedent Moisture Conditions (AMC) for modeling the watershed area. The AMC describe the relative wetness or dryness of the soil and can have significant effects on the runoff volume.

Computer models were used to quantify the impacts of implementing LID and BMP techniques on the campus. Texas A&M employed two companies, TCB, Inc. and Strong Surveying, to undertake the task of building the models of the campus using HEC-HMS and SWMM (described below). They assessed the current conditions and built hydrologic and hydraulic computer models to model the "Present conditions".

HEC-HMS

Hydrologic Modeling System, HEC-HMS, is a free program developed by the U.S. Army Corps of Engineers and is designed to simulate the precipitation-runoff processes of watersheds (U.S. Army Corps of Engineers 2009). The HEC-HMS model of Texas A&M was built by TCB, Inc. with the survey work performed by Strong Surveying. The program uses the Curve Number Method applied to subbasins to determine the runoff volumes for a given precipitation event. The Curve Number Method is based on the subbasins' hydrologic soil group and land use (Mays 2005). The subbasins represented the area that drained to each junction noted in the survey of the watershed.

The Present basin model was modified to represent the other 6 scenarios. The basin models were created by adjusting the curve numbers for the subbasins to reflect the implementation of LID techniques. Table 2 shows the curve number selected for each LID techniques applied in the model as well as the area of the watershed the technique was applied.

LID Technique	Area Applied	Curve Number
Pervious Pavement	14%	77
Green Roofs	7%	86
Rainwater Harvesting	7%	98

Table 2: LID techniques considered in analysis including the area of the basin applied and CN

Pervious pavement and rainwater harvesting were represented with an effective storage of 4 inches. Rainwater harvesting was modeled with the same curve number as an impervious surface because it is assumed that the rainwater hits the rooftop and immediately stored. The storage volumes were modeled as the first 4 inches of rainfall, and any rainfall amount over the storage volume would contribute to the runoff for the basin. This approach was used based on the previous study by Damodaram et al. (2010). The curve numbers chosen for each LID technique were based on literature values and calculations based on design storage volumes and infiltration of Damodaram et al. (2010). The curve numbers were applied to new basin models and the precipitation events were applied to the model. A total of 77 precipitation events were considered in the HEC-HMS model for this study. These events were historical records from 1978 to 2009 and ranged from 2 inches to 15.3 inches. A table of the precipitation events, including the depth of rainfall and duration can be found in Appendix A. The time constraints were set to reflect the date of the precipitation event and the time was extended by 6 hours to ensure the full capture of runoff. The simulation runs were created for each scenario by selecting the desired basin, precipitation event and time frame and computed through HEC-HMS.

SWMM

The second program used in the analysis was the Storm Water Management Model, SWMM, developed by the U.S. Environmental Protection Agency. SWMM is a dynamic rainfall-runoff simulation model used for a single event or long-term simulation of runoff quantity and quality. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators (U.S. Environmental Protection Agency 2010). The SWMM model for the Texas A&M campus was also built by TCB, Inc. with the survey work performed by Strong Surveying. The program uses the network of storm sewers and channels to route the runoff volumes obtained using HEC-HMS. The model consists of the network of links and nodes that represent the different drainage infrastructure across West Campus and can be seen in Figure 3 (TCB 2008). The nodes correspond to the manholes, outfalls, or connection points within the pipe network. The links correspond to storm sewers, culverts, bridges, natural channels, and outfalls. The network has one outfall that represents the runoff volume that enters White Creek.

The SWMM model of the Present hydraulic conditions was used for the scenarios involving the LID techniques as described in Table 1. The same model was used for each of the LID scenarios because the current drainage infrastructure would not be affected by the implementation of the LID techniques. To model the detention basin scenario, the Present condition model was modified to include a detention basin with a storage volume of 73,372 m^3 and maximum depth of 5.4 meters. The hydrologic results from HEC-HMS were imported into the program and the runoff volumes at each node were routed through the hydraulic system to determine the runoff volume and peak flow at the outfall to the White Creek as seen in Figure 1.

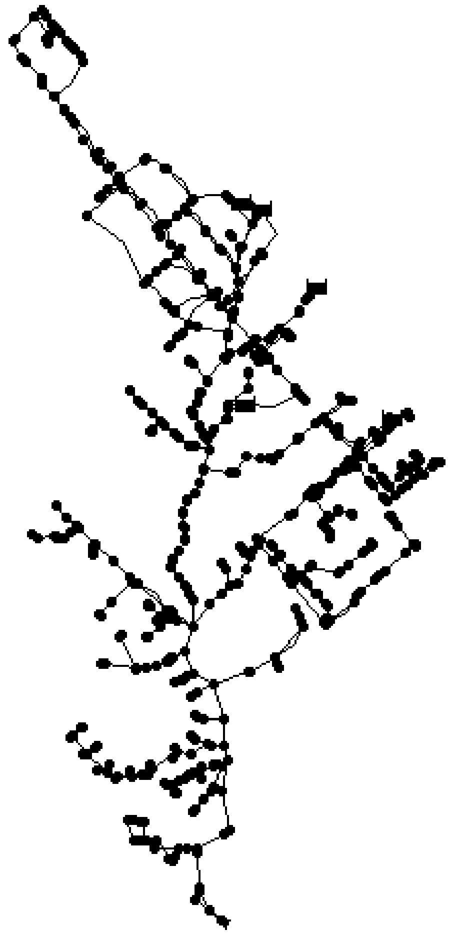


Figure 3: SWMM Network of nodes and links for Texas A&M campus

Hydrologic Footprint Residence

The Hydrologic Footprint Residence uses the output of the hydrologic and hydraulic characteristics of the watershed. The HFR code uses several cross sections of the White Creek to determine the area of the stream and stream banks that would be inundated under each scenario with respect to time. HFR used the runoff volume at the outfall of the SWMM model to calculate the flooding throughout the creek. The output of HFR was a text file showing the inundated area at each time step and also the discharge in the creek at each time step.

Antecedent Moisture Conditions

The second part of the project, evaluating the importance of the antecedent moisture conditions on the runoff volume and peak flow, followed the same general procedure described previously. The HEC-HMS model was adapted to reflect the AMC by modifying the curve number. The Antecedent Moisture Conditions fall under three categories: AMCI, AMCII, and AMCIII. Table 3 shows descriptions and curve numbers used in the model for the three AMC. For reference, impervious surfaces have a CN of 98, whereas grass has a CN of 61 for the location which has primarily Hydrologic Soil Group B (U.S. Natural Resources Conservation Service 2010).

	Description	CN
AMC I	Dry Conditions	58
AMC II	Normal Conditions	77
AMC III	Saturated Conditions	89

Table 3: AMC Conditions and respective Curve Numbers

The curve numbers for the AMC conditions were found using equation (1) and (2) (Singh and Frevert 2006).

$$CN(I) = \frac{4.2[CN(II)]}{10 - 0.058[CN(II)]} \qquad \text{Eq (1)}$$

$$CN(III) = \frac{23[CN(II)]}{10 + 0.13[CN(II)]} \qquad \text{Eq (2)}$$

Once the basin models were adjusted to reflect the AMC conditions, the HEC-HMS model was computed using several design storms. The design storms were 2 year-24 hour, 10 year- 24 hour, and 100 year-24 hour storms for Brazos County and were based on the SCS center-weighted distribution method. There were also two other smaller events. Event 1 is a 36 hour precipitation event and Event 2 is a 30 hour event.

Event	Precipitation (in)
2 yr- 24 hr	4.42
10 yr- 24 hr	7.44
100 yr- 24 hr	11.35
Event 1	0.71
Event 2	1.78

Table 4: Precipitation Events for AMC Conditions

RESULTS

LID and BMP scenarios were simulated and compared to the Present conditions. A table of the peak flow and HFR values for all seven scenarios for the 77 events can be found in Appendix B. The results are compared on the metrics of peak flow, runoff volume, and HFR to show the effectiveness of the LID and BMP techniques to mitigate the effects of urbanization on the watershed. Table 5 shows the nomenclature for Figure 4 through Figure 17.

Scenario	
Present	Present
Green Roof	GR
Rainwater Harvesting	RHS
Pervious Pavement	PP
Green Roof & Pervious Pavement	GRPP
Rainwater Harvesting & Pervious Pavement	RHSPP
Detention Pond	Det

Table 5: Key for Figure 4 through Figure 17

Due to the magnitude of the data set, a representative sample of 10 storms was chosen for analysis. These storms ranged from 2 inches to 15.3 inches in precipitation depth and 2 hours to 25.5 hours in duration. Table 6 shows the representative sample set of storms. For each graph, the events are displayed in order of lowest precipitation depth to highest.

Event	Date	Total Rainfall	Raw Time
73	05Aug2008, 13:30 - 05Aug2008, 18:45	2	4.25
2	03May1979, 22:15 - 04May1979, 04:15	2.2	6
17	25Jun1983, 09:30 - 25Jun1983, 11:30	2.5	2
46	21Jun1993, 13:00 - 21Jun1993, 20:45	2.8	7.75
37	14Jan1991, 17:30 - 14Jan1991, 23:00	3.4	5.5
8	03May1981, 03:45 - 03May1981, 14:30	3.9	10.75
31	25Nov1987, 00:30 - 25Nov1987, 06:15	4.6	5.75
55	12Nov1998, 05:15 - 13Nov1998, 06:45	5.6	25.5
9	12Jun1981, 02:45 - 12Jun1981, 15:00	7.1	12.25
48	16Oct1994, 12:00 - 17Oct1994, 12:00	15.3	24

Table 6: Representative Sample of Storms used in analysis

Peak Flow

Figure 4 shows the results of peak flow for several of the historical events, not including Events 9 and 48, which are the two largest storms in the sample set. The larger events cannot be practically graphed on the same axes without obscuring the relationships of the smaller storms, which are of particular interest in evaluating the effectiveness of LID techniques. The data for this graph is provided in Appendix B. The green roof and pervious pavement combination is the next most effective in lowering the peak flow, followed by pervious pavements, rainwater harvesting, and green roofs. A clear decreasing trend in the peak flow can be seen as the various LID techniques are applied to the watershed. Pervious pavement is the most effective in reducing the peak flow when compared to the scenarios green roofs and rainwater harvesting. Pervious pavement performed more effectively than the other LID techniques, arguably because the paved area is twice the rooftop area in the catchment as seen in Table 2.

Figure 4 can be used to analyze the difference of LID techniques on small and large storms. LID techniques are designed to be most effective for small storms, which is supported by the model results. Analyzing Event 73 (2 inches) and Event 2 (2.2 inches) in more detail (Figure 5) the LID combinations reduce the peak flow more effectively than the detention basin for these smaller events. The larger storms with 2.8 inches to 5.6 inches of precipitation show that the detention pond scenario is most effective in lowering the peak flow for large storms (Figure 6). A more detailed analysis of the differences in small and large storms can be found in Figure 12 and Figure 13.

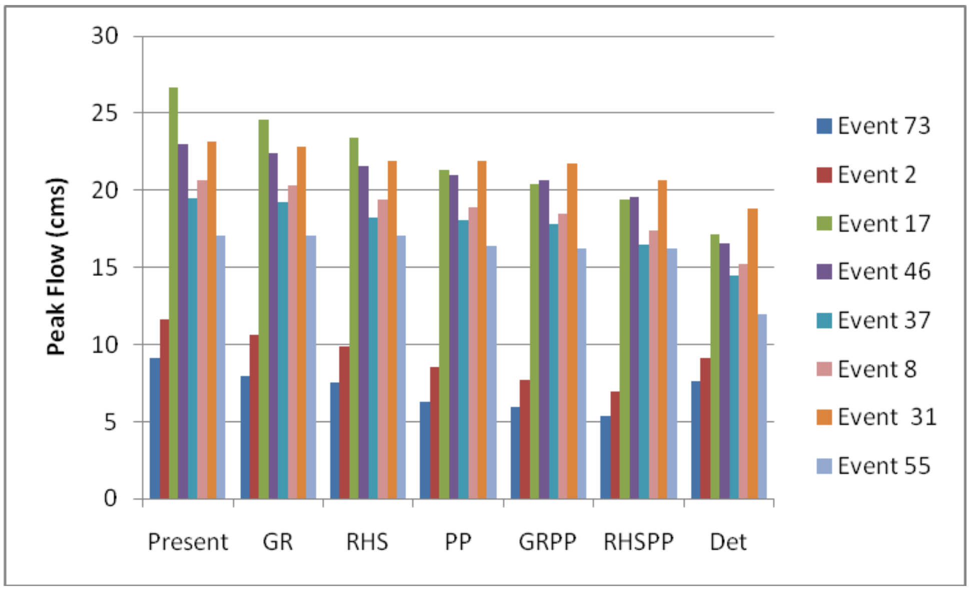


Figure 4: Peak Flow for each scenario for 8 storms

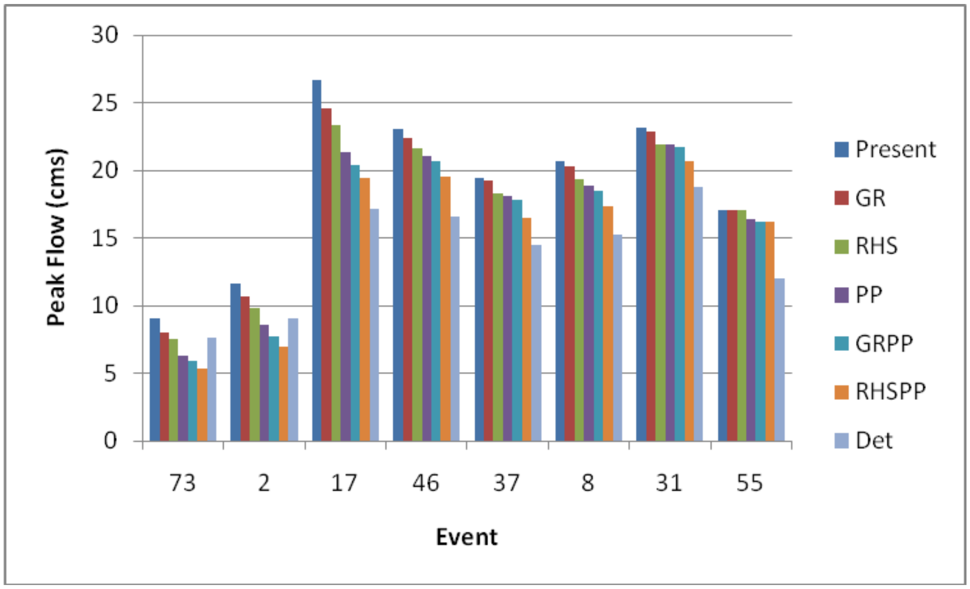


Figure 5: Peak Flow for each scenario for 8 storms

A storm hydrograph can be used to show the effect of storm duration on peak flow values. Precipitation depth has the largest impact on the hydrologic characteristics of a watershed, but Figure 4 also shows other factors play a role. For example, Event 55 has a total precipitation depth of 5.6 inches, but the peak flow value is much smaller than several of the smaller storms including Event 17, which has a total precipitation depth of less than half of Event 55. Table 7 shows the storm duration, max incremental depth of precipitation, and intensity for each of the storms. Comparing the intensities of Event 55 with the previous, smaller events, shows that Event 55 has a lower intensity. Event 55 also has a much longer duration than all the other storms. Therefore, it can be expected that the peak flow of Event 55 would be smaller than storms with higher intensities for shorter durations. Figure 6 shows the hydrographs for each event. A hydrograph illustrates the discharge-time relationship of a storm. The figure clearly shows the difference in length and peak flow between Event 55 and Event 17, 46, 37 and 31. The smaller events have much larger flows that occur over much shorter durations.

Event	Total Rainfall (in)	Duration (hr)	Max Incremental Depth (in)	Max Intensity (in/hr)
73	2	4.25	0.3	1.6
2	2.2	6	0.4	1.6
17	2.5	2	1	4.2
46	2.8	7.75	0.6	2.6
37	3.4	5.5	0.6	1.8
8	3.9	10.75	0.5	2.2
31	4.6	5.75	0.7	3.2
55	5.6	25.5	0.3	1.4

Table 7: Duration, max incremental precipitation depth and max intensity of Events in Figure 4

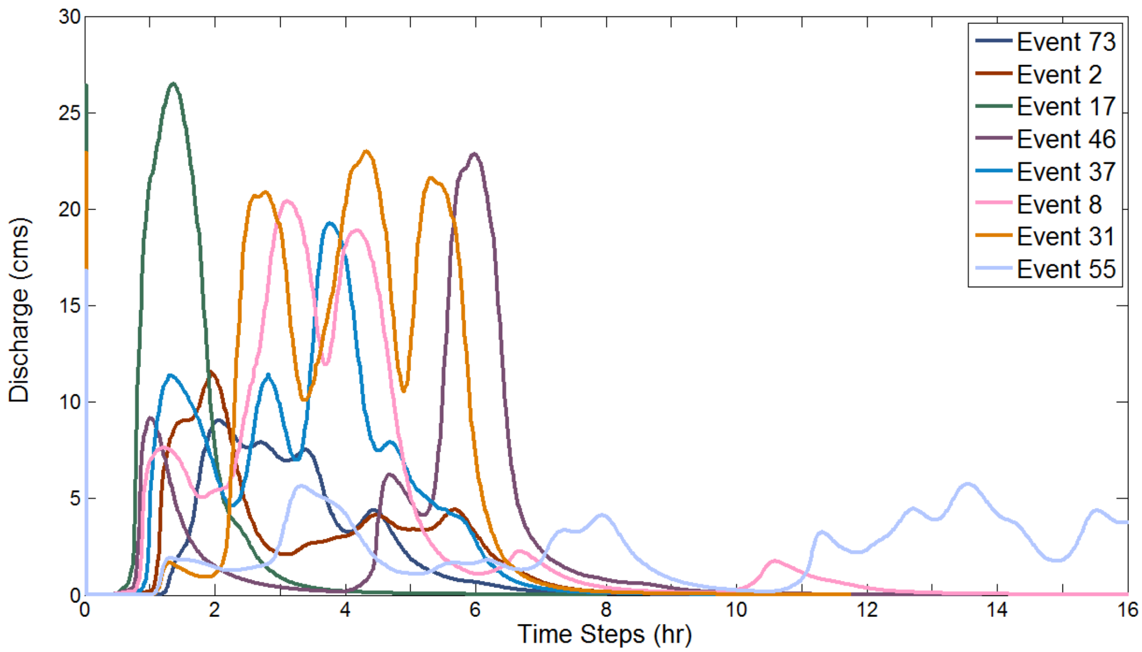


Figure 6: Hydrographs of Storms in Figure 4

Runoff Volume

The runoff volume can also be used to compare the impacts of the selected LID and BMP techniques on the watershed. The total runoff volume for each of the events described in the previous graphs can be found in Appendix B. The LID combination of rainwater harvesting and pervious pavement was the most effective in reducing the total runoff. The LID techniques followed the same trend as peak flow. The detention pond scenarios compared with the Present scenarios shows that detention ponds do not reduce the amount of runoff. Detention ponds only retain the water as storage for a certain amount of time while slowly releasing the runoff volume.

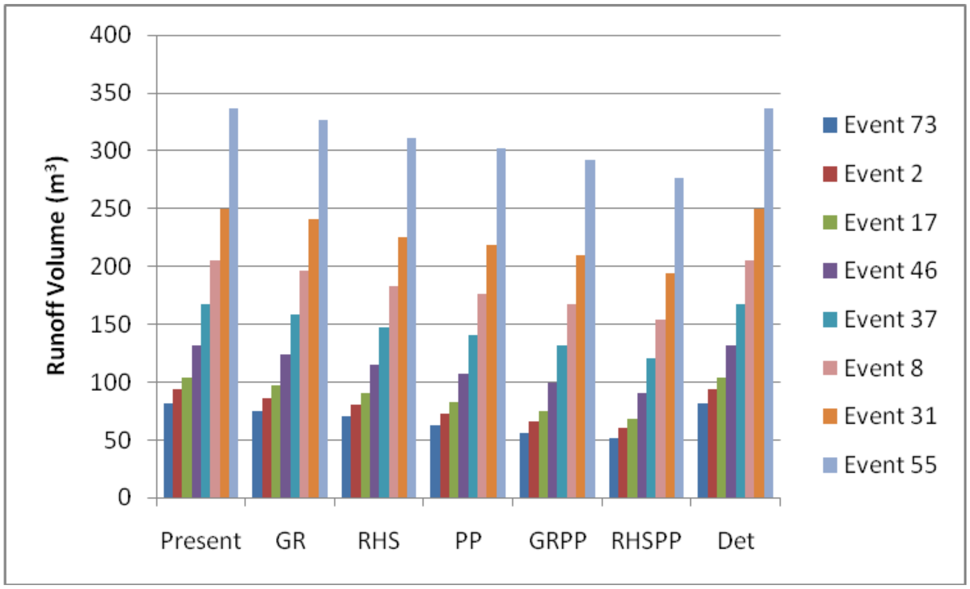


Figure 7: Runoff Volume for each scenario for 8 storms

Hydrologic Footprint Residence

The Hydrologic Footprint Residence is another metric to compare the various scenarios. HFR is designed to capture the temporal and spatial effects of the storm on the watershed (Giacomoni and Zechman 2009). The HFR code developed by Giacomoni and Zechman (2009) computes the temporal evolution of the inundated area as a precursor for the HFR metric, which is the inundation area- duration. That is, the HFR metric is the integrated area under the inundated area-time graph. The integration is a measure of the total area that the stream covers during the storm event and the time that the water remains. It is calculated using the peak flow, stream cross sections, and the duration. HFR is an ideal metric when comparing LID scenarios for the same storm event because the storm characteristics remain constant. Different storms on the same watershed could yield similar HFR results because the HFR value is the integrated area.

Therefore, a storm with a high intensity for a short duration could have the same HFR value as a storm with low intensity for a long duration. This is illustrated in Figure 8.

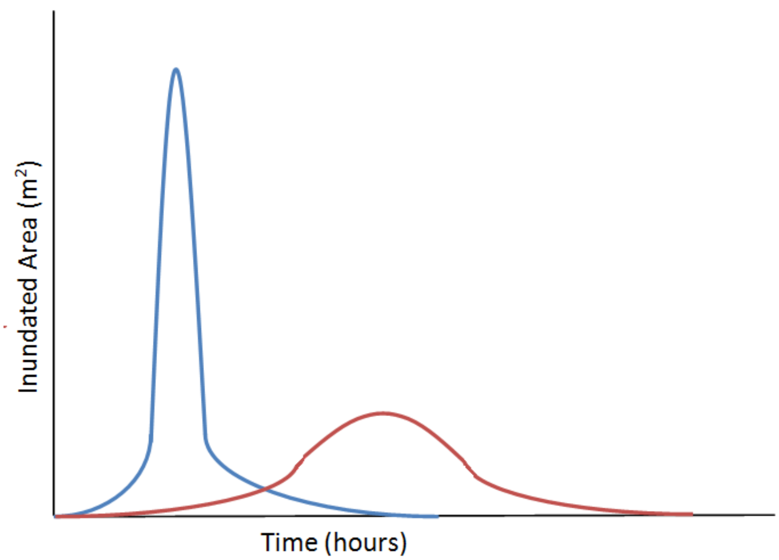


Figure 8: Illustration of HFR for large storm with short durations vs. small storm with long duration

Figure 9 shows the results for the HFR method for Event 73 Present. The total area flooded during the storm was calculated to be 13,729 m^2hr. The HFR for each scenario for Event 73 can be compared in Figure 10. The figure shows how the LID techniques reduce the HFR, with the most effective reduction through the combination of rainwater harvesting and pervious pavements. Figure 11 shows the time series of the inundated area for the watershed. The time series data can show how the LID and BMP techniques reduce the HFR for the scenarios. As shown in both the peak flow and runoff volume graphs, the rainwater harvesting and pervious pavement scenarios are the most effective in reducing the HFR values.

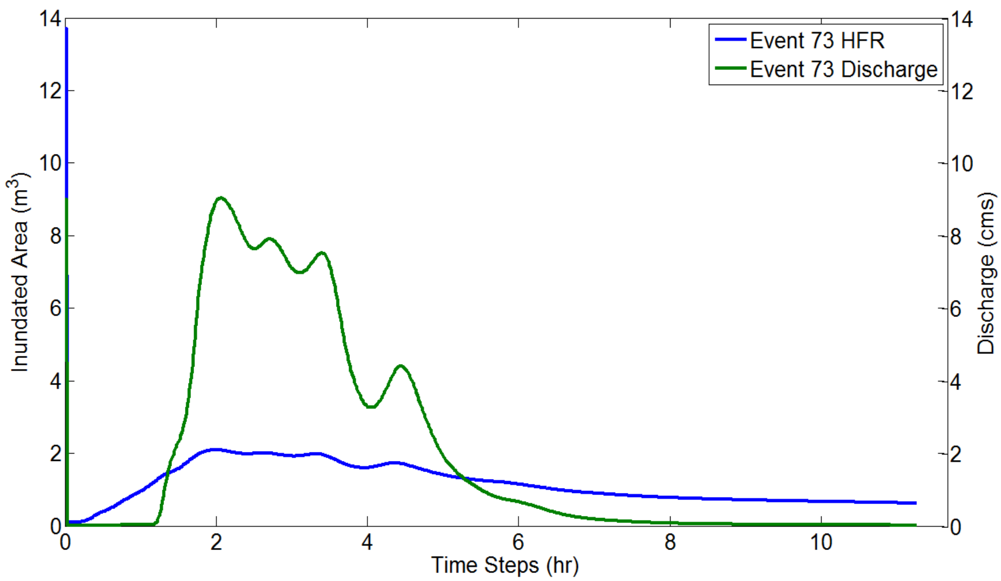


Figure 9: Event 73 Present Scenario time series inundated area and Discharge

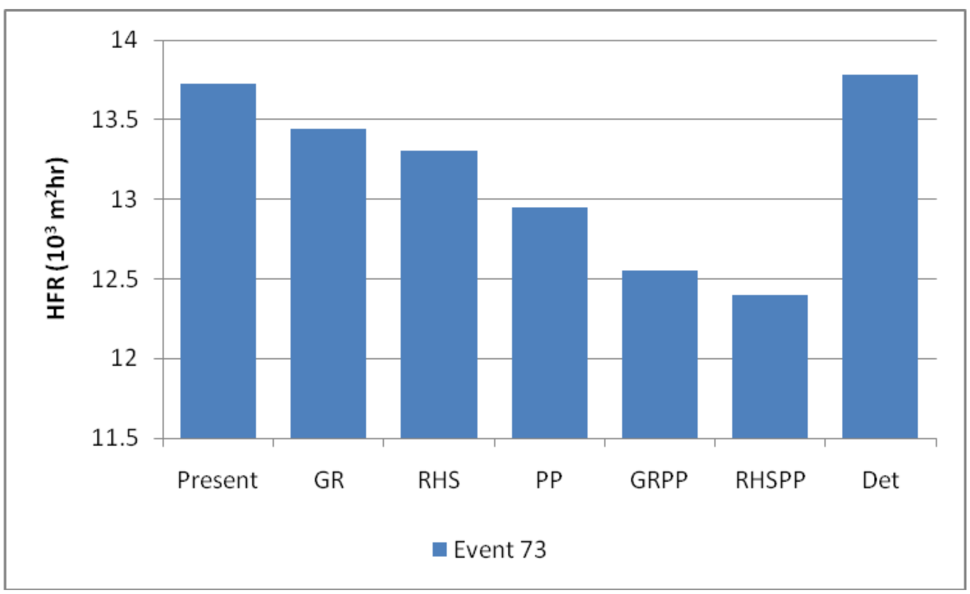


Figure 10: HFR for Event 73

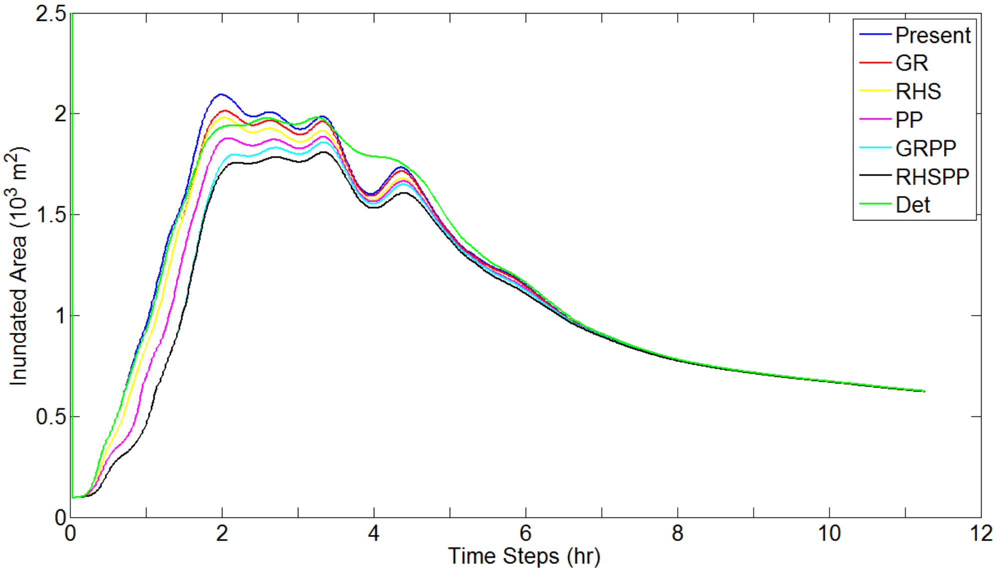


Figure 11: Event 73, time series of inundated area for all scenarios

The HFR can be compared across storms for each scenario as a quantification of the response of the watershed to the different LID and BMP scenarios. Figure 12 shows the HFR values for the same 8 storms compared using peak flow and runoff volume. Using the HFR metric, the rainwater harvesting and pervious pavement combination is most effective in reducing the effects of urbanization on the watershed. The combination scenario green roofs and pervious pavements are the next most effective, followed by pervious pavements alone, rainwater harvesting alone, and green roofs. For every storm, the detention pond scenario is least effective in reducing the inundated areas over the duration of the storms.

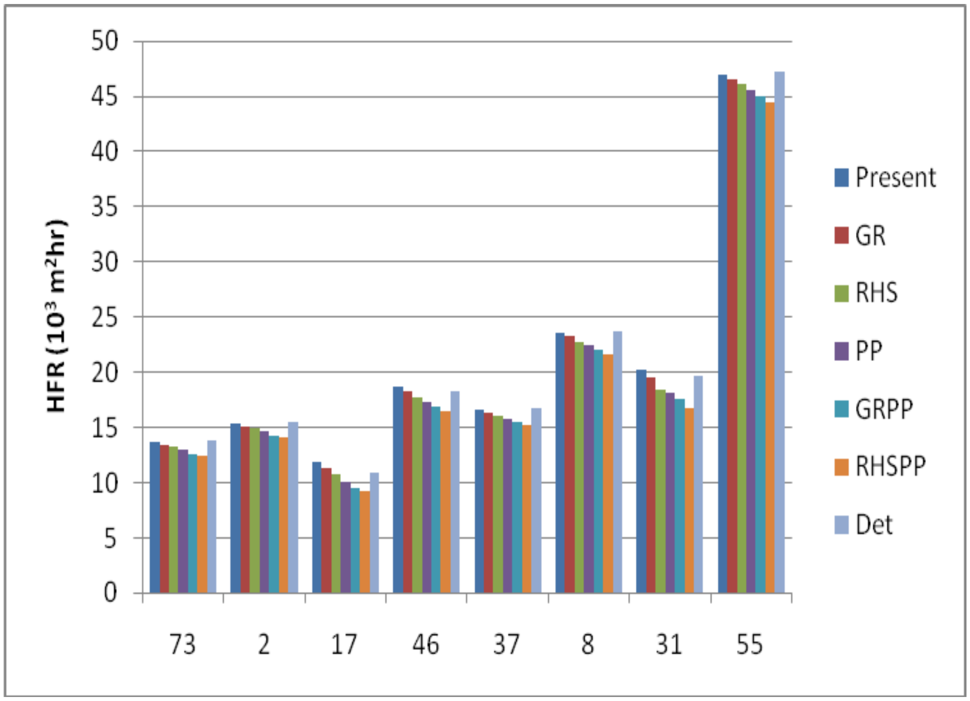


Figure 12: HFR for each scenario for 8 storms

Small vs. Large Storms

The LID techniques can also be analyzed by storm size. For this comparison, small storms are classified as less than 3 inches of precipitation and large storms are all storms with more than 3 inches of precipitation. Note that in literature, small storms are commonly classified as less than 1.6 inches of precipitation (Durrans, Burian, & Pitt, 2009), but this study only considered storms larger than 2 inches of precipitation, so the larger cutoff was chosen to reflect the observed data.

Figure 13 shows the change in peak flow for all 10 of the sample storms. The values in the graph represent the change in peak flow as a percent reduction from the Present Scenario. The generic equation for determining the percent reduction from the Present Scenario is described in Equation 3 below:

$$\left|\frac{(\text{LID Scenario}) - (\text{Present Scenario})}{\text{Present Scenario}}\right| \times 100\% \qquad (\text{Eq. } 3)$$

Events 73 and 2 (the smallest peak flow events) show an increasing trend such that the highest percent reduction is for the LID combination of rainwater harvesting and pervious pavement. For these smaller events, the detention basin provides less than half the reduction achieved by the best LID case. But for the storms larger than 2.2 inches, the detention basin reduces the peak flow more effectively than the LID cases. Events 48 and 9 have 7.1 inches and 15.3 inches of precipitation and are the two largest storms modeled in this study. Figure 13 also shows that for these storms, the LID techniques have very little impact on the peak flow. For these larger storms, the detention basin is extremely effective in reducing the peak flow by over 35%. The detention basin reduces the peak flow for Event 48 by approximately 50%.

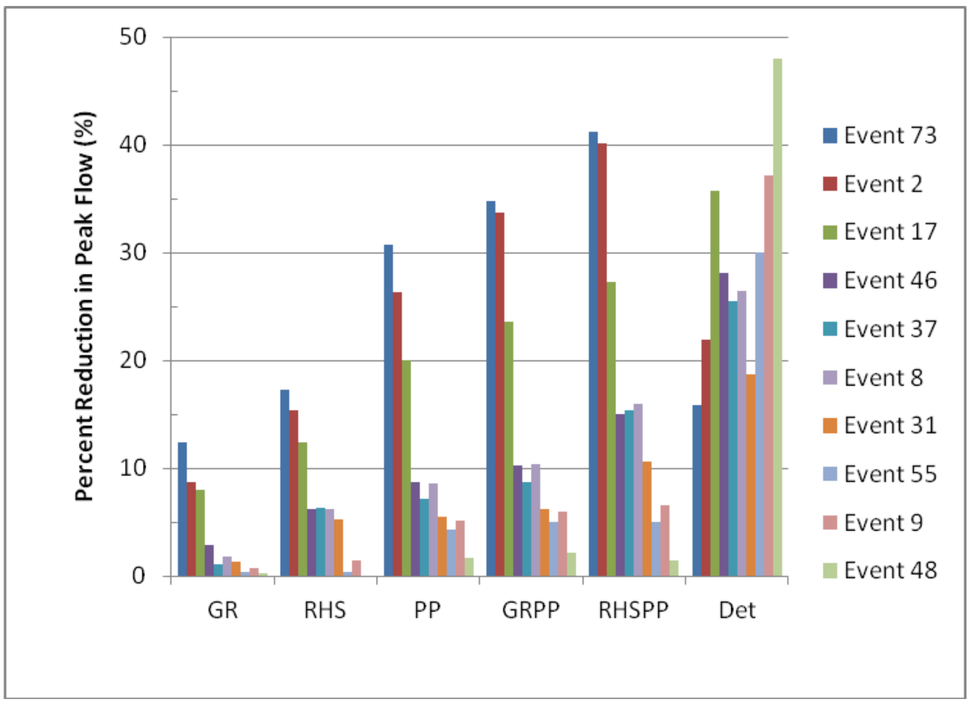


Figure 13: Percent reduction from the Present scenario for Peak Flow

The changes in runoff volumes compared to the Present scenario can also show the effectiveness of techniques for small and large storms. Figure 14 shows the percent reduction from the Present scenario for the runoff volume for each scenario. The detention basin is not designed to reduce the runoff volume, and this is can be seen in the graph in the zero percent change from the Present scenario. Figure 14 also shows the effectiveness of the LID techniques on smaller storms. The smallest storm, Event 73, has the highest percent reduction in runoff volume. As the storms become larger, the percent change reduces, and the LID techniques become increasingly unsuccessful in reducing the runoff volume for the largest storm, Event 48.

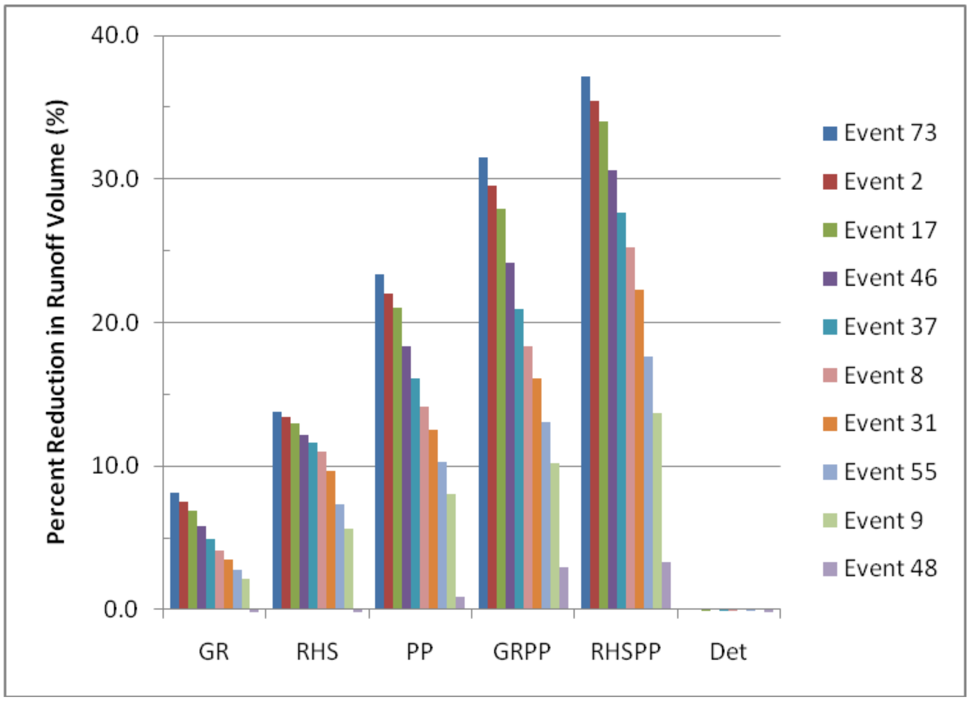
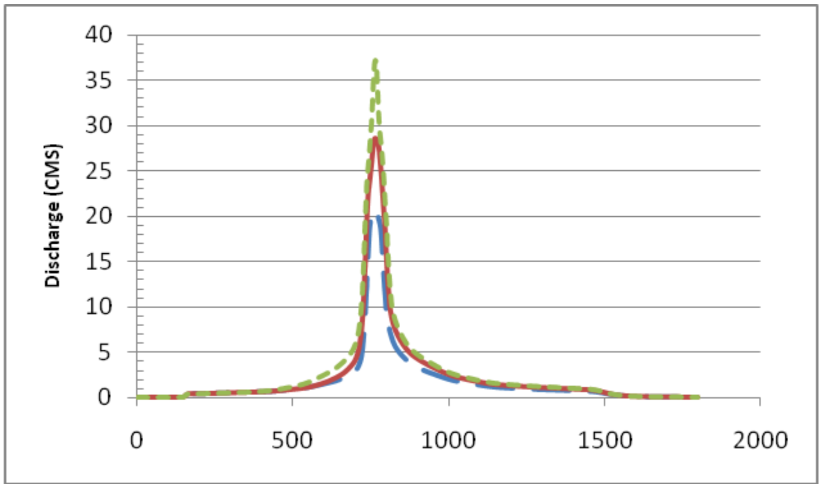
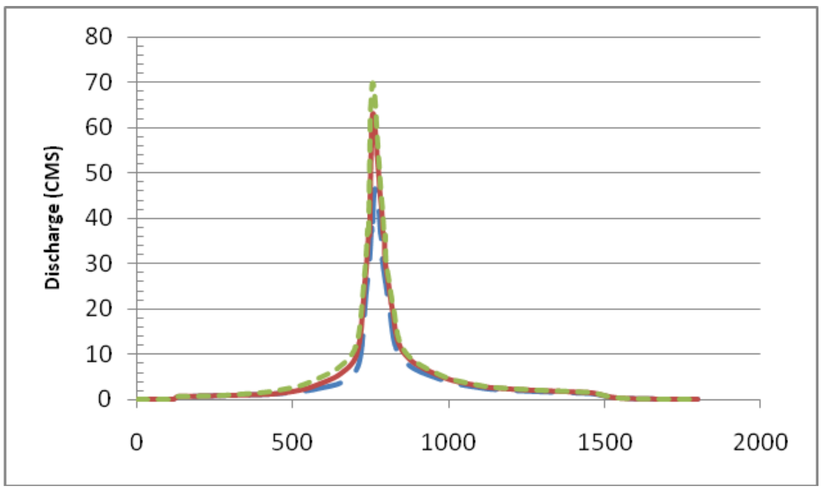


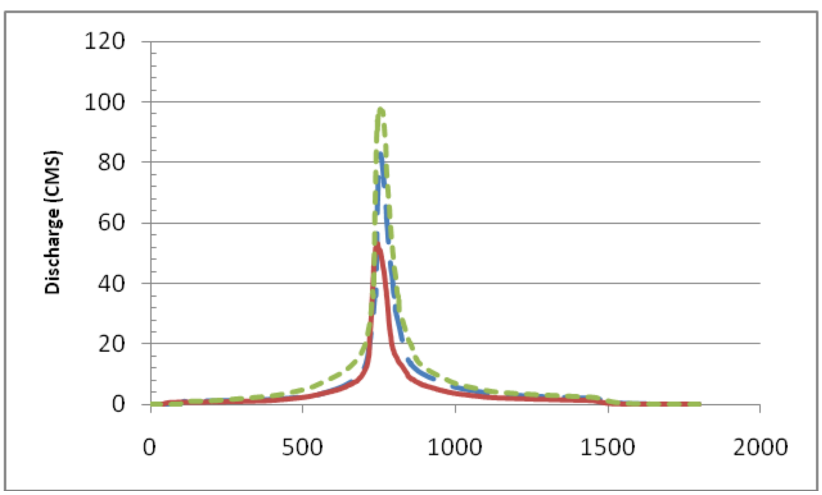
Figure 14: Percent reduction from the Present scenario for Runoff Volume

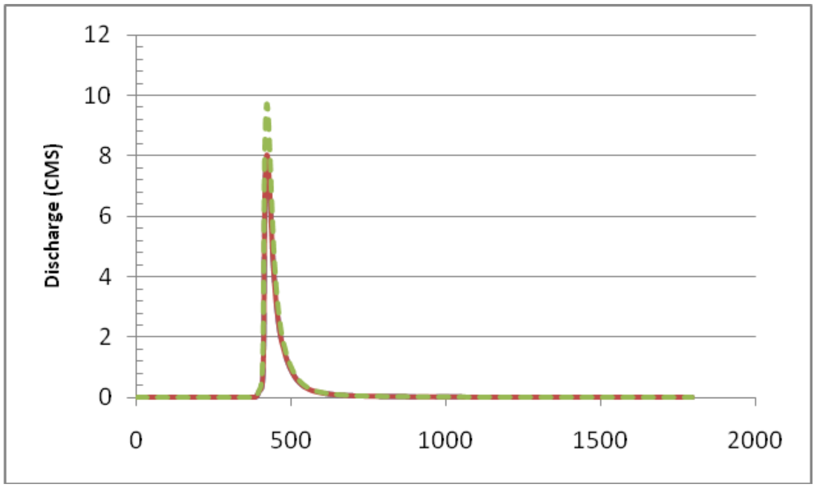
Antecedent Moisture Conditions

The hydrographs for the second part of the project, evaluating the AMC conditions, can be seen in Figure 15. For each event, AMCIII generates the highest peak flow. This is reasonable because AMCIII is the saturated soil condition, and therefore no more water can infiltrate. This results in less infiltration and a higher discharge to the creek.

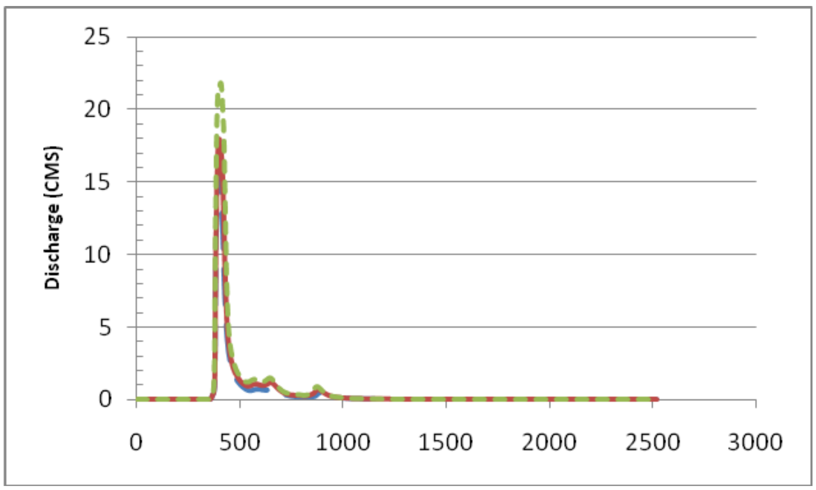

Discharge (CMS)
0
5
10
15
20
25
30
35
40
0
500
1000
1500
2000
(a)


Discharge (CMS)
0
10
20
30
40
50
60
70
80
0
500
1000
1500
2000
(b)


Discharge (CMS)
0
20
40
60
80
100
120
0
500
1000
1500
2000
(c)



(d)



(e)

Figure 15: Hydrographs for Antecedent Moisture Condition scenarios. (a) 2 year- 24 hours design storm, (b) 10 year- 24 hour design storm, (c) 100 year- 24 hour design storm, (d) Event 1, (e) Event 2. The horizontal axis is time steps in minutes. The blue line represents AMCI, the red line represents AMCII, and the green line represents AMCIII.

The percent difference in peak flow for the AMC conditions can be seen in Figure 16. The percent reduction for the AMCI conditions and percent increase for the AMCIII conditions were calculated and compared across the three design storms. For each storm, AMCI had a percent reduction in peak flow from AMCII. AMCI describes a drier soil than AMCII, resulting in a smaller runoff volume and a reduction in the peak flow. For each storm, AMCIII had a percent increase in peak flow from AMCII. AMCIII describes a saturated soil compared to AMCII, resulting in a higher runoff volume, and an increase in peak flow. The 2 year- 24 hour design storm had the highest differences in both AMCI and AMCIII conditions. As seen in the figure, there is a downward trend in percent change as the design storm gets larger. The smallest percent differences were seen in the 100 year- 24 hour event.

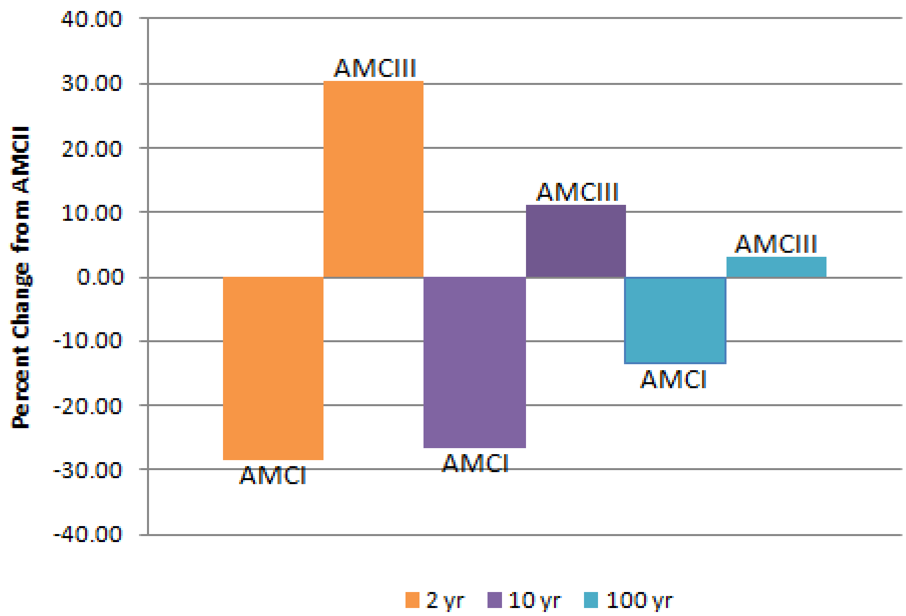
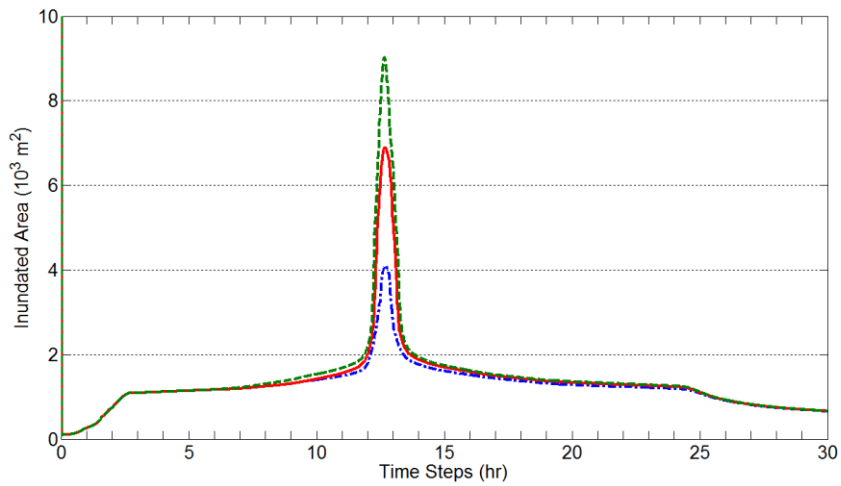
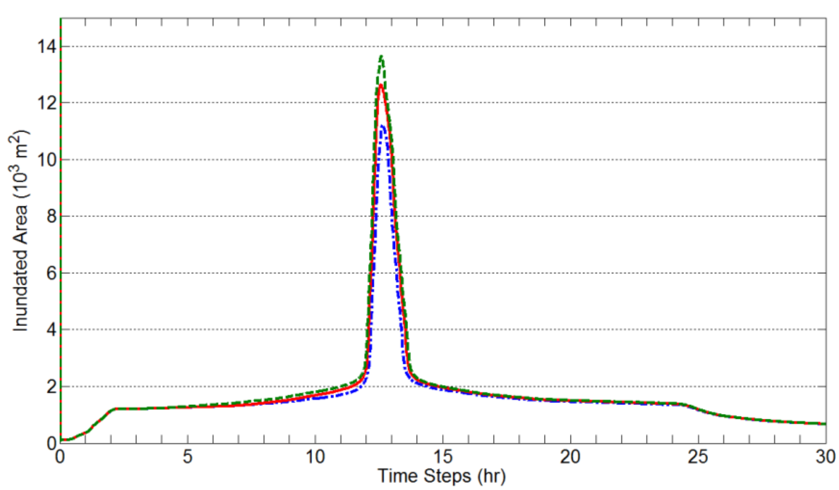
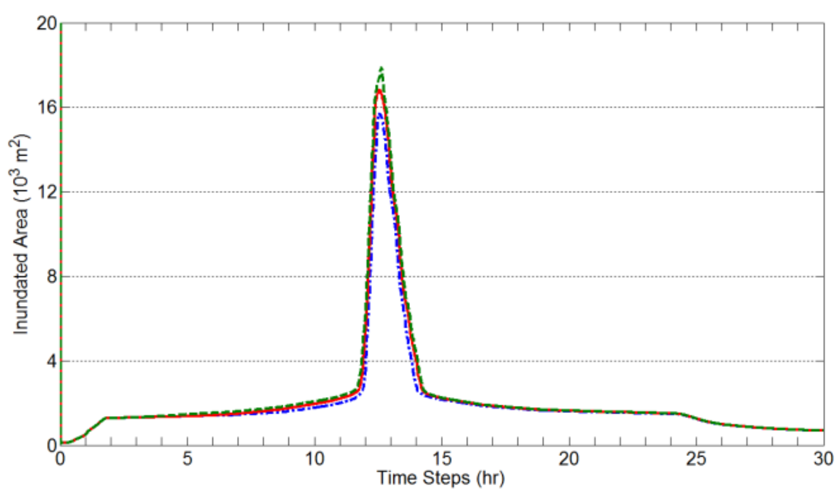


Figure 16: Percent Change in peak flow from AMCII Condition for Design Storms

The AMC conditions can also be compared using the HFR metric. Figure 17 shows HFR graphs for the AMC conditions. For all three design storms and also the two real storms, the AMCIII condition results in the highest HFR values. The smallest HFR values for all the storms were the AMCI conditions.


Inundated Area (10^3 m^2)
Time Steps (hr)
0
2
4
6
8
10
5
15
20
25
30
(a)


Inundated Area (10^3 m^2)
Time Steps (hr)
0
2
4
6
8
10
12
14
5
15
20
25
30
(b)


Inundated Area (10^3 m^2)
Time Steps (hr)
0
4
8
12
16
20
5
10
15
25
30
(c)

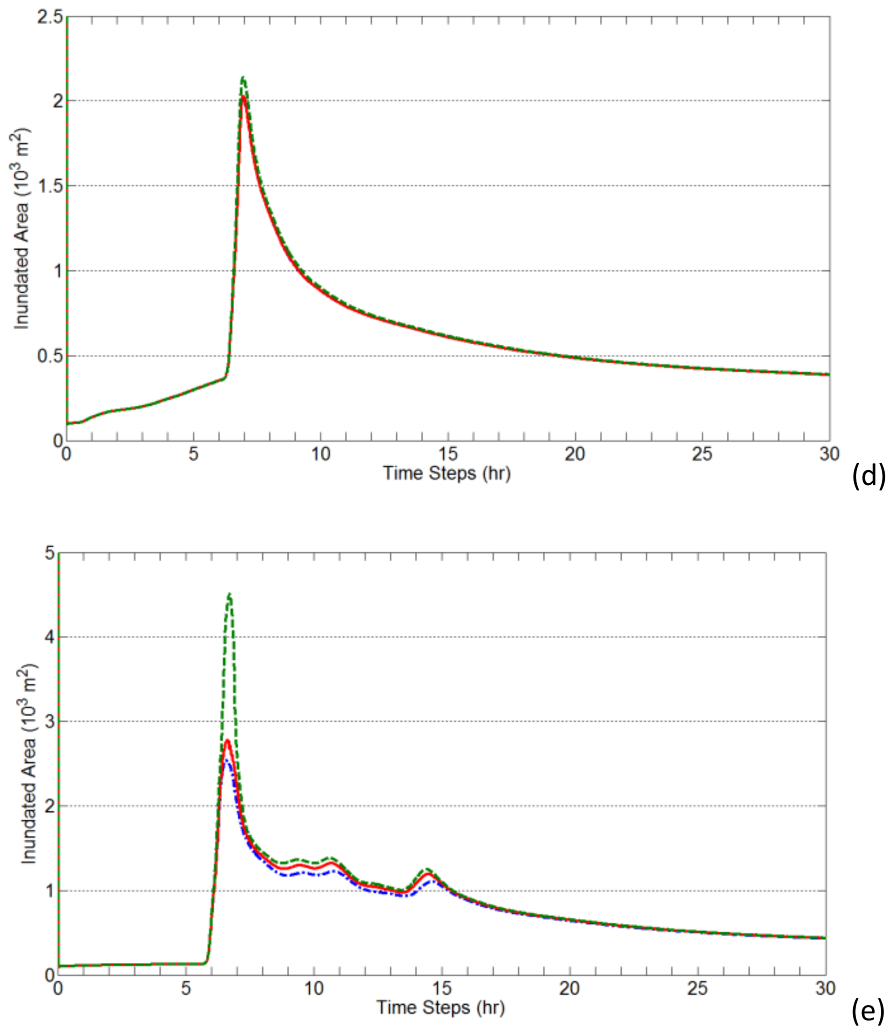


Figure 17: HFR for Antecedent Moisture Condition scenarios. (a) 2 year- 24 hours design storm, (b) 10 year- 24 hour design storm, (c) 100 year- 24 hour design storm, (d) Event 1, (e) Event 2. The horizontal axis is time steps in minutes. The blue line represents AMCI, the red line represents AMCII, and the green line represents AMCIII.

The percent change in HFR for the AMC conditions can be seen in Figure 18. The percent reduction for the AMCI conditions and percent increase for the AMCIII conditions were calculated and compared across the three design storms. As seen in the peak flow analysis, AMCI had a percent reduction for HFR and AMCIII had a percent increase for HFR when compared to AMCII. The 2 year- 24 hour design storm had the highest differences in the AMCIII condition, but the 100 year storm had the highest percent change in the AMCI condition. As seen in the figure, there is a downward trend in percent change as the design storm gets larger for the AMCIII conditions. The AMCI conditions do not follow the same trend as the storm size increases. The percent changes for the AMC conditions are very small; the average percent change was 6.4%. Since the values in percent change from the AMCII condition are small, one can conclude that AMC conditions do not play an important role in the duration and inundated area of the watershed during a storm.

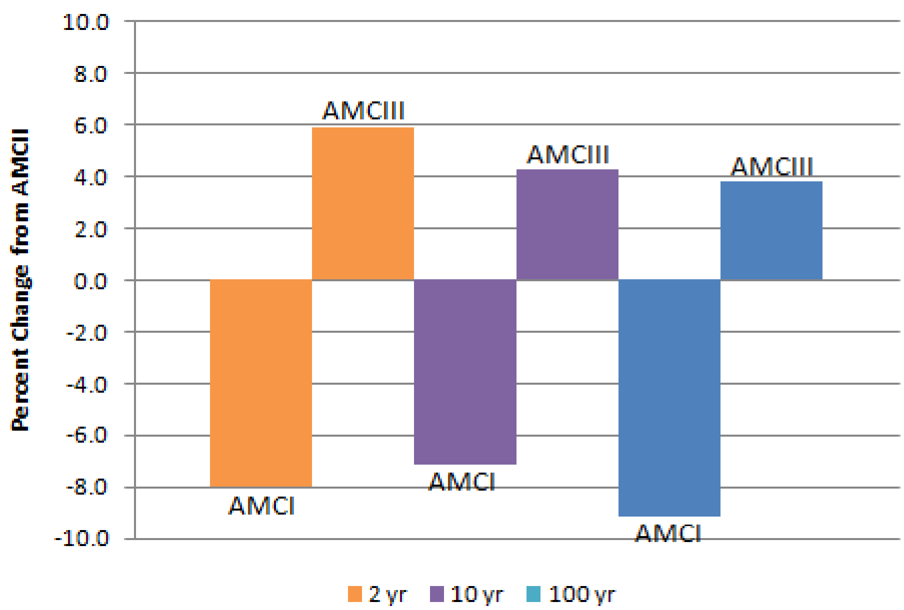


Figure 18: Percent change in HFR for the AMC conditions

SUMMARY & CONCLUSIONS

This study evaluated the effectiveness of LID and BMP techniques on reducing the impacts of urbanization on the White Creek watershed on Texas A&M University's West Campus. The LID techniques evaluated were green roofs, rainwater harvesting and pervious pavements, and the combination green roofs with pervious pavements, and rainwater harvesting with pervious pavements. The BMP technique evaluated was a detention pond. The techniques were evaluated on several metrics including the standard peak flow and runoff volume. The third metric compared was the Hydrologic Footprint Residence (HFR). HFR is a new metric developed by Giacomoni and Zechman (2009) from Texas A&M University that better characterizes the downstream effects of urbanization on a watershed. HFR incorporates the quantity of flow from the storm with the duration of the storm and the cross sections of the stream being analyzed. The techniques were evaluated using 77 historical storm events from 1978 to 2009. These storms ranged in precipitation depths from 2 inches to 15.3 inches and 1.25 hours to 25.5 hours in duration.

A sample of 10 storms was used in the analysis of the LID and BMP techniques. These storms were chosen to more effectively quantify the impacts of those techniques on the White Creek watershed. In general, the scenario that was the most effective in lowering the peak flow, runoff volume, and HFR of the storm was the combination of rainwater harvesting and pervious pavements. The detention pond was shown to effectively lower the peak flow for larger storms, but does not change the runoff volume of any storm. The LID techniques were shown to be more effective in reducing the impacts of urbanization for small storms. The results also gave insight into the importance of the precipitation intensity and duration.

The importance of the Antecedent Moisture Condition of the soil was also studied. The AMC describes the moisture of the soil, ranging from dry (AMCI) to saturated (AMCIII). The AMCs were evaluated using the 24 hour design storms 2 year, 10 year, and 100 year. Two other smaller historical events were also used, with precipitation depths of 0.71 inches and 1.78 inches. The AMC was found to have an impact on the peak flows with AMCIII resulting in the highest peak flow for each storm event and AMCI resulting in lowest peak flow. The largest percent difference in peak flows was found in the smaller storms, and decreased as the storm size increased. Similar results were shown in the HFR results. The highest HFR value was the AMCIII conditions, followed by AMCII and AMCI. When comparing the percent differences between the scenarios, AMCIII was the highest.

The increasing trend in urbanization is shown to have numerous adverse effects on the hydrology of watersheds. This study looks into the potential benefits of Low Impact Development retrofit techniques that can be implemented in urban environments. LID techniques have been shown to be a tool to minimize the urban effects on a watershed. Through HEC-HMS and SWMM models, this study reinforced those previous findings using a large range of historical storms as an alternative of the traditional design storms. Although BMPs are the conventional methods in stormwater management, LID techniques may be more effective in returning a watershed to predevelopment hydrologic regimes.

Appendix A

Historical Precipitation Events

Name	Date and Time	Rainfall Depth (inches)	Time (hours)
Event1	11Sep1978, 22:45 - 12Sep1978,	3.2	9.25
Event2	03May1979, 22:15 - 04May1979,	2.2	6
Event3	30May1979, 16:30 - 30May1979,	2.4	1.25
Event4	07Jul1979, 13:45 - 07Jul1979, 16:45	2.7	3
Event5	19Sep1979, 06:45 - 20Sep1979,	4.2	19.5
Event6	15May1980, 03:45 - 15May1980,	3.2	12
Event7	19Jan1981, 05:30 - 20Jan1981,	2	19
Event8	03May1981, 03:45 - 03May1981,	3.9	10.75
Event9	12Jun1981, 02:45 - 12Jun1981,	7.1	12.25
Event10	30Aug1981, 17:15 - 31Aug1981,	2.3	21.5
Event11	31Oct1981, 02:15 - 31Oct1981,	4.8	10.5
Event12	08Nov1981, 12:00 - 08Nov1981,	2.1	3.25
Event13	20Apr1982, 10:45 - 20Apr1982,	2.1	12.25
Event14	13May1982, 02:00 - 13May1982,	2.4	11.75
Event15	23Mar1983, 05:45 - 23Mar1983,	3	7.5
Event16	19May1983, 22:00 - 20May1983,	4.8	19
Event17	25Jun1983, 09:30 - 25Jun1983,	2.5	2
Event18	07Aug1983, 16:45 - 07Aug1983,	2.3	2.25
Event19	08Aug1983, 04:15 - 08Aug1983,	2.2	4.75
Event20	18Sep1983, 13:15 - 19Sep1983,	2.5	16.75
Event21	27Jul1984, 16:30 - 27Jul1984, 20:30	3	4
Event22	23Feb1985, 07:45 - 23Feb1985,	2.3	4.5
Event23	18Jun1985, 13:45 - 18Jun1985,	2.4	5.25
Event24	29Sep1985, 08:30 - 29Sep1985,	3.7	13.75
Event25	01May1986, 06:15 - 01May1986,	2	5.5
Event26	08Jun1986, 06:30 - 08Jun1986,	2.5	2.5
Event27	14Dec1986, 07:30 - 15Dec1986,	2.5	24.5
Event28	29May1987, 02:00 - 29May1987,	2.9	11.75
Event29	31May1987, 18:15 - 31May1987,	2	5.25
Event30	12Jun1987, 11:15 - 12Jun1987,	2.3	3.75
Event31	25Nov1987, 00:30 - 25Nov1987,	4.6	5.75
Event32	17Mar1988, 11:00 - 17Mar1988,	2.4	7.5
Event33	28Mar1989, 11:30 - 28Mar1989,	2.7	6.5
Event34	11Jun1989, 03:15 - 11Jun1989,	3	4
Event35	18Jan1990, 02:00 - 18Jan1990,	2.2	1.75
Event36	26Dec1990, 10:30 - 26Dec1990,	2.2	11
Event37	14Jan1991, 17:30 - 14Jan1991,	3.4	5.5
Event38	18Jan1991, 04:45 - 18Jan1991,	2.6	6.75
Event39	21Dec1991, 03:00 - 21Dec1991,	3.8	17.5
Event40	03Feb1992, 02:15 - 03Feb1992,	2.9	21.5
Event41	01Nov1992, 02:30 - 01Nov1992,	2	6.5

Historical Precipitation Events (continued)

Name	Date and Time	Rainfall Depth (inches)	Time (hours)
Event42	19Nov1992, 12:45 - 19Nov1992,	2.4	9
Event43	14Dec1992, 06:15 - 15Dec1992,	4.1	25.25
Event44	19Mar1993, 18:30 - 19Mar1993,	2.9	3.5
Event45	19Jun1993, 09:00 - 20Jun1993,	6	21.25
Event46	21Jun1993, 13:00 - 21Jun1993,	2.8	7.75
Event47a	20Oct1993, 00:00 - 20Oct1993,	5.4	20
Event48a	16Oct1994, 12:00 - 17Oct1994,	15.3	24
Event49	17Jan1995, 14:45 - 17Jan1995,	2.9	7.5
Event50	26Jan1995, 09:00 - 26Jan1995,	2	8.25
Event51	30Jul1995, 16:45 - 31Jul1995, 03:00	2.9	10.25
Event52	02Oct1995, 20:00 - 02Oct1995,	2.3	2.5
Event53	18Dec1995, 02:30 - 18Dec1995,	2.2	2.25
Event54	12Feb1997, 03:30 - 12Feb1997,	1.9	18.5
Event55	12Nov1998, 05:15 - 13Nov1998,	5.6	25.5
Event56	01May2000, 03:00 - 01May2000,	2.3	9.75
Event57	13Oct2001, 00:00 - 13Oct2001,	3	8.5
Event58	16Jul2002, 07:30 - 16Jul2002, 11:45	2.4	4.25
Event59	09Oct2002, 06:30 - 09Oct2002,	2.1	5.75
Event60	19Oct2002, 07:30 - 19Oct2002,	2.2	7.25
Event61	09Oct2003, 12:00 - 09Oct2003,	2.1	4.5
Event62	23Jun2004, 14:30 - 23Jun2004,	2.1	4.5
Event63	27Jun2004, 00:45 - 27Jun2004,	2.5	6.25
Event64	22Nov2004, 06:00 - 22Nov2004,	2.7	11.75
Event65	10Oct2005, 06:45 - 10Oct2005,	2.9	4.75
Event66	17Jun2006, 07:45 - 17Jun2006,	2.2	3.75
Event67	19Jun2006, 22:45 - 20Jun2006,	2.1	9
Event68	18Sep2006, 02:30 - 18Sep2006,	2	4.25
Event69	15Oct2006, 23:30 - 16Oct2006,	2.4	9
Event70	13Jan2007, 16:00 - 14Jan2007,	5.5	9.75
Event71	05May2008, 04:30 - 05May2008,	6.5	11.25
Event72	29Jun2008, 17:45 - 29Jun2008,	2.3	4.25
Event73	05Aug2008, 13:30 - 05Aug2008,	2	5.25
Event74	13Sep2008, 00:45 - 13Sep2008,	3.3	15.5
Event75	11Nov2008, 10:15 - 11Nov2008,	3.1	13.5
Event76	17Apr2009, 03:15 - 17Apr2009,	2.5	5.5
Event77	17Apr2009, 23:15 - 18Apr2009,	2.4	4.25

* Note that the storm events are named sequentially by date.

Appendix B

Peak Discharge and HFR Value

Storm Event	Rainfall Depth (inches)	Peak Flow (cms)	HFR (m^2hr)	Storm Event	Rainfall Depth (inches)	Peak Flow (cms)	HFR (m^2hr)
Event_1_Present	3.2	18.72	19.98	Event_6_Present	3.2	20.64	23.77
Event_1_GR	3.2	17.84	19.59	Event_6_GR	3.2	20.33	23.39
Event_1_RHS	3.2	16.86	19.29	Event_6_RHS	3.2	19.42	22.97
Event_1_PP	3.2	16.01	18.90	Event_6_PP	3.2	18.96	22.60
Event_1_GRPP	3.2	15.66	18.39	Event_6_GRPP	3.2	18.63	22.16
Event_1_RHSPP	3.2	14.29	18.09	Event_6_RHSPP	3.2	17.51	21.80
Event_1_Det	3.2	13.80	20.30	Event_6_Det	3.2	14.33	24.13
Event_2_Present	2.2	11.66	15.34	Event_7_Present	2	2.77	29.34
Event_2_GR	2.2	10.65	15.10	Event_7_GR	2	2.46	28.82
Event_2_RHS	2.2	9.87	14.92	Event_7_RHS	2	2.27	28.55
Event_2_PP	2.2	8.59	14.61	Event_7_PP	2	1.92	27.86
Event_2_GRPP	2.2	7.73	14.28	Event_7_GRPP	2	1.65	27.09
Event_2_RHSPP	2.2	6.97	14.08	Event_7_RHSPP	2	1.49	26.74
Event_2_Det	2.2	9.10	15.46	Event_7_Det	2	2.64	29.38
Event_3_Present	2.4	27.87	11.20	Event_8_Present	3.9	20.66	23.55
Event_3_GR	2.4	26.63	10.59	Event_8_GR	3.9	20.30	23.24
Event_3_RHS	2.4	24.38	10.07	Event_8_RHS	3.9	19.38	22.69
Event_3_PP	2.4	22.80	9.36	Event_8_PP	3.9	18.88	22.46
Event_3_GRPP	2.4	21.28	8.85	Event_8_GRPP	3.9	18.51	22.10
Event_3_RHSPP	2.4	20.25	8.40	Event_8_RHSPP	3.9	17.37	21.67
Event_3_Det	2.4	18.62	10.05	Event_8_Det	3.9	15.21	23.68
Event_4_Present	2.7	23.70	12.81	Event_9_Present	7.1	51.82	38.61
Event_4_GR	2.7	22.81	12.41	Event_9_GR	7.1	51.43	38.19
Event_4_RHS	2.7	21.49	11.84	Event_9_RHS	7.1	51.06	37.11
Event_4_PP	2.7	20.86	11.39	Event_9_PP	7.1	49.17	36.79
Event_4_GRPP	2.7	20.31	11.05	Event_9_GRPP	7.1	48.74	36.34
Event_4_RHSPP	2.7	19.16	10.72	Event_9_RHSPP	7.1	48.42	35.30
Event_4_Det	2.7	17.28	12.43	Event_9_Det	7.1	32.57	34.62
Event_5_Present	4.2	12.69	36.03	Event_10_Present	2.3	5.67	32.71
Event_5_GR	4.2	12.19	35.54	Event_10_GR	2.3	5.44	32.09
Event_5_RHS	4.2	11.42	35.11	Event_10_RHS	2.3	5.00	31.82
Event_5_PP	4.2	10.76	34.57	Event_10_PP	2.3	4.70	31.01
Event_5_GRPP	4.2	10.30	33.81	Event_10_GRPP	2.3	4.47	30.06
Event_5_RHSPP	4.2	9.28	33.35	Event_10_RHSPP	2.3	4.05	29.74
Event_5_Det	4.2	9.95	36.15	Event_10_Det	2.3	5.37	32.80

Peak Discharge and HFR Value (continued)

Storm Event	Rainfall Depth (inches)	Peak Flow (cms)	HFR (m^2hr)	Storm Event	Rainfall Depth (inches)	Peak Flow (cms)	HFR (m^2hr)
Event_11_Present	4.8	21.17	26.25	Event_16_Present	4.8	19.20	36.70
Event_11_GR	4.8	20.97	25.86	Event_16_GR	4.8	19.06	36.41
Event_11_RHS	4.8	19.62	25.24	Event_16_RHS	4.8	18.03	35.92
Event_11_PP	4.8	20.04	24.89	Event_16_PP	4.8	18.20	35.66
Event_11_GRPP	4.8	19.88	24.38	Event_16_GRPP	4.8	18.07	35.34
Event_11_RHSPP	4.8	18.49	23.86	Event_16_RHSPP	4.8	16.79	34.86
Event_11_Det	4.8	15.33	26.50	Event_16_Det	4.8	13.14	37.30
Event_12_Present	2.1	16.71	11.82	Event_17_Present	2.5	26.70	11.92
Event_12_GR	2.1	15.44	11.62	Event_17_GR	2.5	24.56	11.32
Event_12_RHS	2.1	14.52	11.47	Event_17_RHS	2.5	23.38	10.72
Event_12_PP	2.1	12.61	11.24	Event_17_PP	2.5	21.35	10.09
Event_12_GRPP	2.1	11.52	11.00	Event_17_GRPP	2.5	20.40	9.52
Event_12_RHSPP	2.1	10.29	10.84	Event_17_RHSPP	2.5	19.40	9.22
Event_12_Det	2.1	11.01	11.99	Event_17_Det	2.5	17.17	10.87
Event_13_Present	2.1	8.88	21.96	Event_18_Present	2.3	25.87	11.97
Event_13_GR	2.1	8.12	21.66	Event_18_GR	2.3	23.97	11.42
Event_13_RHS	2.1	7.46	21.44	Event_18_RHS	2.3	22.69	10.86
Event_13_PP	2.1	6.58	21.10	Event_18_PP	2.3	21.01	10.28
Event_13_GRPP	2.1	6.24	20.70	Event_18_GRPP	2.3	20.05	9.78
Event_13_RHSPP	2.1	5.44	20.44	Event_18_RHSPP	2.3	19.08	9.49
Event_13_Det	2.1	6.34	22.12	Event_18_Det	2.3	17.28	10.98
Event_14_Present	2.4	12.01	22.49	Event_19_Present	2.2	16.85	13.21
Event_14_GR	2.4	11.53	22.08	Event_19_GR	2.2	15.81	12.93
Event_14_RHS	2.4	10.39	21.84	Event_19_RHS	2.2	14.73	12.79
Event_14_PP	2.4	9.32	21.30	Event_19_PP	2.2	13.30	12.42
Event_14_GRPP	2.4	8.12	21.34	Event_19_GRPP	2.2	12.33	12.03
Event_14_RHSPP	2.4	7.66	20.38	Event_19_RHSPP	2.2	11.39	11.87
Event_14_Det	2.4	8.25	22.62	Event_19_Det	2.2	11.76	13.38
Event_15_Present	3	15.46	19.13	Event_20_Present	2.5	9.26	28.34
Event_15_GR	3	14.74	18.86	Event_20_GR	2.5	9.03	28.02
Event_15_RHS	3	13.64	18.59	Event_20_RHS	2.5	8.22	27.69
Event_15_PP	3	12.53	18.25	Event_20_PP	2.5	8.14	27.31
Event_15_GRPP	3	11.81	17.84	Event_20_GRPP	2.5	7.95	26.88
Event_15_RHSPP	3	10.63	17.57	Event_20_RHSPP	2.5	7.15	26.50
Event_15_Det	3	11.37	19.24	Event_20_Det	2.5	7.52	28.52

Peak Discharge and HFR Value (continued)

Storm Event	Rainfall Depth (inches)	Peak Flow (cms)	HFR (m^2hr)	Storm Event	Rainfall Depth (inches)	Peak Flow (cms)	HFR (m^2hr)
Event_21_Present	3	20.83	13.89	Event_26_Present	2.5	27.10	12.68
Event_21_GR	3	20.29	13.57	Event_26_GR	2.5	25.16	12.17
Event_21_RHS	3	19.45	13.22	Event_26_RHS	2.5	23.50	11.57
Event_21_PP	3	18.60	12.95	Event_26_PP	2.5	21.92	10.95
Event_21_GRPP	3	18.06	12.69	Event_26_GRPP	2.5	21.18	10.41
Event_21_RHSPP	3	16.88	12.46	Event_26_RHSPP	2.5	20.07	9.96
Event_21_Det	3	15.76	14.05	Event_26_Det	2.5	18.84	11.69
Event_22_Present	2.3	15.83	13.35	Event_27_Present	2.5	7.00	36.89
Event_22_GR	2.3	14.92	13.14	Event_27_GR	2.5	6.79	36.21
Event_22_RHS	2.3	13.82	12.97	Event_27_RHS	2.5	6.22	35.88
Event_22_PP	2.3	12.68	12.71	Event_27_PP	2.5	6.05	34.97
Event_22_GRPP	2.3	11.89	12.43	Event_27_GRPP	2.5	5.85	33.91
Event_22_RHSPP	2.3	10.77	12.25	Event_27_RHSPP	2.5	5.27	33.53
Event_22_Det	2.3	11.62	13.65	Event_27_Det	2.5	5.88	36.97
Event_23_Present	2.4	17.69	14.98	Event_28_Present	2.9	16.01	22.72
Event_23_GR	2.4	17.16	14.76	Event_28_GR	2.9	14.56	22.36
Event_23_RHS	2.4	16.14	14.56	Event_28_RHS	2.9	13.80	22.09
Event_23_PP	2.4	15.18	14.30	Event_28_PP	2.9	11.75	21.69
Event_23_GRPP	2.4	14.39	14.03	Event_28_GRPP	2.9	9.88	21.14
Event_23_RHSPP	2.4	12.92	13.83	Event_28_RHSPP	2.9	8.93	20.84
Event_23_Det	2.4	11.99	15.15	Event_28_Det	2.9	10.01	22.82
Event_24_Present	3.7	17.95	27.27	Event_29_Present	2	14.36	13.50
Event_24_GR	3.7	17.56	26.92	Event_29_GR	2	13.71	13.29
Event_24_RHS	3.7	16.31	26.52	Event_29_RHS	2	12.53	13.14
Event_24_PP	3.7	15.86	26.26	Event_29_PP	2	11.90	12.90
Event_24_GRPP	3.7	15.39	25.84	Event_29_GRPP	2	11.42	12.62
Event_24_RHSPP	3.7	13.93	25.42	Event_29_RHSPP	2	10.04	12.46
Event_24_Det	3.7	11.80	27.67	Event_29_Det	2	9.84	13.72
Event_25_Present	2	11.74	14.52	Event_30_Present	2.3	18.73	12.67
Event_25_GR	2	11.40	14.29	Event_30_GR	2.3	18.31	12.44
Event_25_RHS	2	10.18	14.14	Event_30_RHS	2.3	17.37	12.27
Event_25_PP	2	9.32	13.83	Event_30_PP	2.3	16.59	11.99
Event_25_GRPP	2	8.71	13.50	Event_30_GRPP	2.3	16.00	11.70
Event_25_RHSPP	2	7.82	13.33	Event_30_RHSPP	2.3	14.54	11.55
Event_25_Det	2	8.29	14.65	Event_30_Det	2.3	13.26	13.11

Peak Discharge and HFR Value (continued)

Storm Event	Rainfall Depth (inches)	Peak Flow (cms)	HFR (m^2hr)	Storm Event	Rainfall Depth (inches)	Peak Flow (cms)	HFR (m^2hr)
Event_31_Present	4.6	23.17	20.27	Event_36_Present	2.2	7.24	21.64
Event_31_GR	4.6	22.80	19.54	Event_36_GR	2.2	6.92	21.24
Event_31_RHS	4.6	21.90	18.45	Event_36_RHS	2.2	6.36	21.03
Event_31_PP	4.6	21.88	18.09	Event_36_PP	2.2	6.09	20.50
Event_31_GRPP	4.6	21.69	17.53	Event_36_GRPP	2.2	5.88	19.92
Event_31_RHSPP	4.6	20.65	16.81	Event_36_RHSPP	2.2	5.29	19.65
Event_31_Det	4.6	18.81	19.65	Event_36_Det	2.2	5.88	21.71
Event_32_Present	2.4	12.51	16.59	Event_37_Present	3.4	19.48	16.65
Event_32_GR	2.4	11.86	16.22	Event_37_GR	3.4	19.27	16.39
Event_32_RHS	2.4	10.93	16.07	Event_37_RHS	3.4	18.26	16.07
Event_32_PP	2.4	10.44	15.57	Event_37_PP	3.4	18.08	15.81
Event_32_GRPP	2.4	9.97	14.97	Event_37_GRPP	3.4	17.78	15.50
Event_32_RHSPP	2.4	9.03	14.81	Event_37_RHSPP	3.4	16.49	15.22
Event_32_Det	2.4	10.26	16.73	Event_37_Det	3.4	14.51	16.82
Event_33_Present	2.7	13.10	17.04	Event_38_Present	2.6	9.51	16.75
Event_33_GR	2.7	12.75	16.82	Event_38_GR	2.6	9.01	16.45
Event_33_RHS	2.7	11.82	16.58	Event_38_RHS	2.6	8.33	16.25
Event_33_PP	2.7	11.71	16.32	Event_38_PP	2.6	7.77	15.88
Event_33_GRPP	2.7	11.55	16.02	Event_38_GRPP	2.6	7.31	15.44
Event_33_RHSPP	2.7	10.13	15.76	Event_38_RHSPP	2.6	6.62	15.22
Event_33_Det	2.7	9.89	17.22	Event_38_Det	2.6	8.23	16.80
Event_34_Present	3	28.98	16.38	Event_39_Present	3.8	8.59	33.93
Event_34_GR	3	28.25	15.68	Event_39_GR	3.8	8.20	33.62
Event_34_RHS	3	25.70	14.98	Event_39_RHS	3.8	7.52	33.13
Event_34_PP	3	24.53	14.30	Event_39_PP	3.8	7.02	32.86
Event_34_GRPP	3	23.08	13.67	Event_39_GRPP	3.8	6.66	32.44
Event_34_RHSPP	3	21.39	12.94	Event_39_RHSPP	3.8	5.95	31.93
Event_34_Det	3	19.49	14.13	Event_39_Det	3.8	6.76	34.04
Event_35_Present	2.2	22.88	10.48	Event_40_Present	2.9	10.98	33.11
Event_35_GR	2.2	21.25	9.99	Event_40_GR	2.9	10.68	32.60
Event_35_RHS	2.2	20.67	9.51	Event_40_RHS	2.9	9.81	32.26
Event_35_PP	2.2	19.20	9.06	Event_40_PP	2.9	9.40	31.65
Event_35_GRPP	2.2	18.33	8.77	Event_40_GRPP	2.9	9.06	30.83
Event_35_RHSPP	2.2	17.22	8.63	Event_40_RHSPP	2.9	8.22	30.45
Event_35_Det	2.2	15.52	10.23	Event_40_Det	2.9	8.80	33.20

Peak Discharge and HFR Value (continued)

Storm Event	Rainfall Depth (inches)	Peak Flow (cms)	HFR (m^2hr)	Storm Event	Rainfall Depth (inches)	Peak Flow (cms)	HFR (m^2hr)
Event_41_Present	2	18.09	15.51	Event_46_Present	2.8	23.02	18.71
Event_41_GR	2	16.90	15.26	Event_46_GR	2.8	22.37	18.32
Event_41_RHS	2	16.16	15.08	Event_46_RHS	2.8	21.59	17.77
Event_41_PP	2	14.06	14.82	Event_46_PP	2.8	21.03	17.35
Event_41_GRPP	2	12.42	14.55	Event_46_GRPP	2.8	20.67	16.91
Event_41_RHSPP	2	11.53	14.35	Event_46_RHSPP	2.8	19.57	16.52
Event_41_Det	2	12.02	15.03	Event_46_Det	2.8	16.55	18.31
Event_42_Present	2.4	13.66	19.44	Event_47_Present	5.4	25.79	39.37
Event_42_GR	2.4	12.50	19.14	Event_47_GR	5.4	24.90	38.75
Event_42_RHS	2.4	11.71	18.89	Event_47_RHS	5.4	23.13	37.70
Event_42_PP	2.4	10.11	18.53	Event_47_PP	5.4	22.86	37.15
Event_42_GRPP	2.4	8.99	18.11	Event_47_GRPP	5.4	22.27	36.31
Event_42_RHSPP	2.4	8.14	17.84	Event_47_RHSPP	5.4	21.24	35.33
Event_42_Det	2.4	9.70	19.57	Event_47_Det	5.4	19.76	37.79
Event_43_Present	4.1	9.00	44.22	Event_48_Present	15.3	80.50	82.24
Event_43_GR	4.1	8.67	43.79	Event_48_GR	15.3	80.30	85.03
Event_43_RHS	4.1	7.93	43.20	Event_48_RHS	15.3	80.59	84.32
Event_43_PP	4.1	7.53	42.79	Event_48_PP	15.3	79.17	83.34
Event_43_GRPP	4.1	7.20	42.17	Event_48_GRPP	15.3	78.75	82.02
Event_43_RHSPP	4.1	6.51	41.54	Event_48_RHSPP	15.3	79.30	81.92
Event_43_Det	4.1	7.03	44.37	Event_48_Det	15.3	41.89	70.63
Event_44_Present	2.9	20.26	13.19	Event_49_Present	2.9	19.69	17.94
Event_44_GR	2.9	19.44	12.82	Event_49_GR	2.9	19.35	17.61
Event_44_RHS	2.9	18.71	12.53	Event_49_RHS	2.9	18.27	17.30
Event_44_PP	2.9	17.22	12.22	Event_49_PP	2.9	18.03	16.97
Event_44_GRPP	2.9	16.22	11.93	Event_49_GRPP	2.9	17.67	16.55
Event_44_RHSPP	2.9	14.83	11.74	Event_49_RHSPP	2.9	16.31	16.28
Event_44_Det	2.9	14.05	13.35	Event_49_Det	2.9	14.06	18.16
Event_45_Present	6	22.41	39.84	Event_50_Present	2	7.78	17.60
Event_45_GR	6	22.37	24.26	Event_50_GR	2	7.40	17.28
Event_45_RHS	6	22.37	24.26	Event_50_RHS	2	6.80	17.09
Event_45_PP	6	21.93	38.06	Event_50_PP	2	6.37	16.66
Event_45_GRPP	6	21.85	37.21	Event_50_GRPP	2	5.98	16.18
Event_45_RHSPP	6	21.59	36.71	Event_50_RHSPP	2	5.37	15.97
Event_45_Det	6	16.20	39.85	Event_50_Det	2	6.83	17.64

Peak Discharge and HFR Value (continued)

Storm Event	Rainfall Depth (inches)	Peak Flow (cms)	HFR (m^2hr)	Storm Event	Rainfall Depth (inches)	Peak Flow (cms)	HFR (m^2hr)
Event_51_Present	2.9	19.44	21.35	Event_56_Present	2.3	13.69	19.65
Event_51_GR	2.9	19.14	20.89	Event_56_GR	2.3	12.26	19.41
Event_51_RHS	2.9	18.09	20.60	Event_56_RHS	2.3	11.86	19.18
Event_51_PP	2.9	17.74	20.03	Event_56_PP	2.3	9.63	18.91
Event_51_GRPP	2.9	17.37	19.37	Event_56_GRPP	2.3	8.06	18.60
Event_51_RHSPP	2.9	15.94	19.11	Event_56_RHSPP	2.3	7.32	18.33
Event_51_Det	2.9	13.26	21.65	Event_56_Det	2.3	9.21	19.78
Event_52_Present	2.3	22.89	11.72	Event_57_Present	3	18.48	19.83
Event_52_GR	2.3	21.31	11.21	Event_57_GR	3	17.86	19.50
Event_52_RHS	2.3	20.67	10.72	Event_57_RHS	3	16.87	19.21
Event_52_PP	2.3	19.29	10.29	Event_57_PP	3	15.73	18.86
Event_52_GRPP	2.3	18.43	10.00	Event_57_GRPP	3	14.94	18.45
Event_52_RHSPP	2.3	17.32	9.82	Event_57_RHSPP	3	13.52	18.17
Event_52_Det	2.3	15.58	11.25	Event_57_Det	3	13.42	19.96
Event_53_Present	2.2	20.07	10.33	Event_58_Present	2.4	22.59	13.92
Event_53_GR	2.2	19.13	9.97	Event_58_GR	2.4	21.38	13.45
Event_53_RHS	2.2	18.43	9.77	Event_58_RHS	2.4	20.77	12.93
Event_53_PP	2.2	16.74	9.48	Event_58_PP	2.4	19.49	12.45
Event_53_GRPP	2.2	15.34	9.24	Event_58_GRPP	2.4	18.81	12.03
Event_53_RHSPP	2.2	14.03	9.11	Event_58_RHSPP	2.4	17.78	11.82
Event_53_Det	2.2	13.46	10.56	Event_58_Det	2.4	16.31	13.38
Event_54_Present	1.9	4.52	28.72	Event_59_Present	2.1	19.23	13.78
Event_54_GR	1.9	4.21	28.26	Event_59_GR	2.1	18.55	13.46
Event_54_RHS	1.9	3.90	27.99	Event_59_RHS	2.1	17.61	13.28
Event_54_PP	1.9	3.40	27.40	Event_59_PP	2.1	16.32	12.98
Event_54_GRPP	1.9	3.04	26.67	Event_59_GRPP	2.1	15.28	12.64
Event_54_RHSPP	1.9	2.72	26.36	Event_59_RHSPP	2.1	13.92	12.47
Event_54_Det	1.9	4.35	28.78	Event_59_Det	2.1	13.22	14.00
Event_55_Present	5.6	17.09	47.00	Event_60_Present	2.2	7.04	17.21
Event_55_GR	5.6	17.03	46.58	Event_60_GR	2.2	6.62	16.93
Event_55_RHS	5.6	17.03	46.10	Event_60_RHS	2.2	6.10	16.76
Event_55_PP	5.6	16.36	45.57	Event_60_PP	2.2	5.53	16.39
Event_55_GRPP	5.6	16.24	44.97	Event_60_GRPP	2.2	5.13	16.01
Event_55_RHSPP	5.6	16.23	44.45	Event_60_RHSPP	2.2	4.62	15.80
Event_55_Det	5.6	11.97	47.22	Event_60_Det	2.2	5.96	17.29

Peak Discharge and HFR Value (continued)

Storm Event	Rainfall Depth (inches)	Peak Flow (cms)	HFR (m^2hr)	Storm Event	Rainfall Depth (inches)	Peak Flow (cms)	HFR (m^2hr)
Event_61_Present	2.1	16.90	12.36	Event_66_Present	2.2	14.21	12.48
Event_61_GR	2.1	16.34	12.04	Event_66_GR	2.2	13.68	12.26
Event_61_RHS	2.1	15.18	11.94	Event_66_RHS	2.2	17.34	13.31
Event_61_PP	2.1	14.32	11.49	Event_66_PP	2.2	11.94	11.82
Event_61_GRPP	2.1	13.57	10.96	Event_66_GRPP	2.2	11.61	11.51
Event_61_RHSPP	2.1	12.31	10.86	Event_66_RHSPP	2.2	10.30	11.37
Event_61_Det	2.1	12.61	12.77	Event_66_Det	2.2	10.57	12.80
Event_62_Present	2.1	18.89	12.88	Event_67_Present	2.1	10.37	17.67
Event_62_GR	2.1	18.14	12.59	Event_67_GR	2.1	9.18	17.30
Event_62_RHS	2.1	17.29	12.42	Event_67_RHS	2.1	8.60	17.14
Event_62_PP	2.1	15.73	12.11	Event_67_PP	2.1	7.74	16.66
Event_62_GRPP	2.1	14.46	11.76	Event_67_GRPP	2.1	7.43	16.06
Event_62_RHSPP	2.1	13.09	11.61	Event_67_RHSPP	2.1	6.72	15.88
Event_62_Det	2.1	12.71	12.98	Event_67_Det	2.1	8.58	17.78
Event_63_Present	2.5	14.90	14.82	Event_68_Present	2	11.62	12.51
Event_63_GR	2.5	14.43	14.52	Event_68_GR	2	10.20	12.26
Event_63_RHS	2.5	13.32	14.38	Event_68_RHS	2	9.61	12.12
Event_63_PP	2.5	12.90	13.96	Event_68_PP	2	7.98	11.78
Event_63_GRPP	2.5	12.45	13.50	Event_68_GRPP	2	6.82	11.43
Event_63_RHSPP	2.5	11.52	13.35	Event_68_RHSPP	2	6.22	11.30
Event_63_Det	2.5	11.80	15.27	Event_68_Det	2	8.25	12.58
Event_64_Present	2.7	6.89	23.62	Event_69_Present	2.4	19.00	18.62
Event_64_GR	2.7	6.16	23.25	Event_69_GR	2.4	18.45	18.15
Event_64_RHS	2.7	5.68	22.97	Event_69_RHS	2.4	17.40	17.95
Event_64_PP	2.7	5.40	22.51	Event_69_PP	2.4	16.58	17.36
Event_64_GRPP	2.7	5.25	21.98	Event_69_GRPP	2.4	15.94	16.65
Event_64_RHSPP	2.7	4.78	21.68	Event_69_RHSPP	2.4	14.48	16.48
Event_64_Det	2.7	5.68	23.70	Event_69_Det	2.4	12.82	19.01
Event_65_Present	2.9	18.18	14.33	Event_70_Present	5.5	20.12	25.68
Event_65_GR	2.9	17.36	14.01	Event_70_GR	5.5	19.86	25.27
Event_65_RHS	2.9	16.45	13.80	Event_70_RHS	5.5	18.88	24.81
Event_65_PP	2.9	14.90	13.41	Event_70_PP	5.5	18.65	24.39
Event_65_GRPP	2.9	13.74	12.98	Event_70_GRPP	5.5	18.35	23.89
Event_65_RHSPP	2.9	12.48	12.78	Event_70_RHSPP	5.5	17.20	23.54
Event_65_Det	2.9	12.46	14.66	Event_70_Det	5.5	15.75	26.21

Peak Discharge and HFR Value (continued)

Storm Event	Rainfall Depth (inches)	Peak Flow (cms)	HFR (m^2hr)	Storm Event	Rainfall Depth (inches)	Peak Flow (cms)	HFR (m^2hr)
Event_71_Present	6.5	30.20	32.09	Event_76_Present	2.5	17.00	14.88
Event_71_GR	6.5	29.59	31.33	Event_76_GR	2.5	16.25	14.57
Event_71_RHS	6.5	26.99	30.27	Event_76_RHS	2.5	15.15	14.40
Event_71_PP	6.5	26.38	29.45	Event_76_PP	2.5	14.02	14.00
Event_71_GRPP	6.5	25.78	28.61	Event_76_GRPP	2.5	13.14	13.56
Event_71_RHSPP	6.5	23.59	27.51	Event_76_RHSPP	2.5	11.94	13.38
Event_71_Det	6.5	19.39	28.73	Event_76_Det	2.5	12.17	15.02
Event_72_Present	2.3	25.66	13.96	Event_77_Present	2.4	16.38	13.19
Event_72_GR	2.3	23.93	13.41	Event_77_GR	2.4	16.04	12.93
Event_72_RHS	2.3	22.56	12.82	Event_77_RHS	2.4	14.82	12.78
Event_72_PP	2.3	21.00	12.26	Event_77_PP	2.4	14.44	12.42
Event_72_GRPP	2.3	20.07	11.75	Event_77_GRPP	2.4	13.94	12.05
Event_72_RHSPP	2.3	19.13	11.45	Event_77_RHSPP	2.4	12.60	11.89
Event_72_Det	2.3	17.53	12.94	Event_77_Det	2.4	11.85	13.47
Event_73_Present	2	9.10	13.73				
Event_73_GR	2	7.97	13.44				
Event_73_RHS	2	7.53	13.30				
Event_73_PP	2	6.30	12.95				
Event_73_GRPP	2	5.94	12.55				
Event_73_RHSPP	2	5.35	12.40				
Event_73_Det	2	7.66	13.78				
Event_74_Present	3.3	5.02	18.09				
Event_74_GR	3.3	4.23	17.80				
Event_74_RHS	3.3	4.00	17.74				
Event_74_PP	3.3	3.23	17.36				
Event_74_GRPP	3.3	2.63	16.97				
Event_74_RHSPP	3.3	2.40	16.85				
Event_74_Det	3.3	4.56	18.13				
Event_75_Present	3.1	16.56	26.02				
Event_75_GR	3.1	15.14	25.73				
Event_75_RHS	3.1	14.40	25.39				
Event_75_PP	3.1	12.80	25.13				
Event_75_GRPP	3.1	12.60	24.82				
Event_75_RHSPP	3.1	11.57	24.45				
Event_75_Det	3.1	10.48	26.44				

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